Thirty Years Reporting on NASA's Earth Science Program

The Earth Observer

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Editor's Corner

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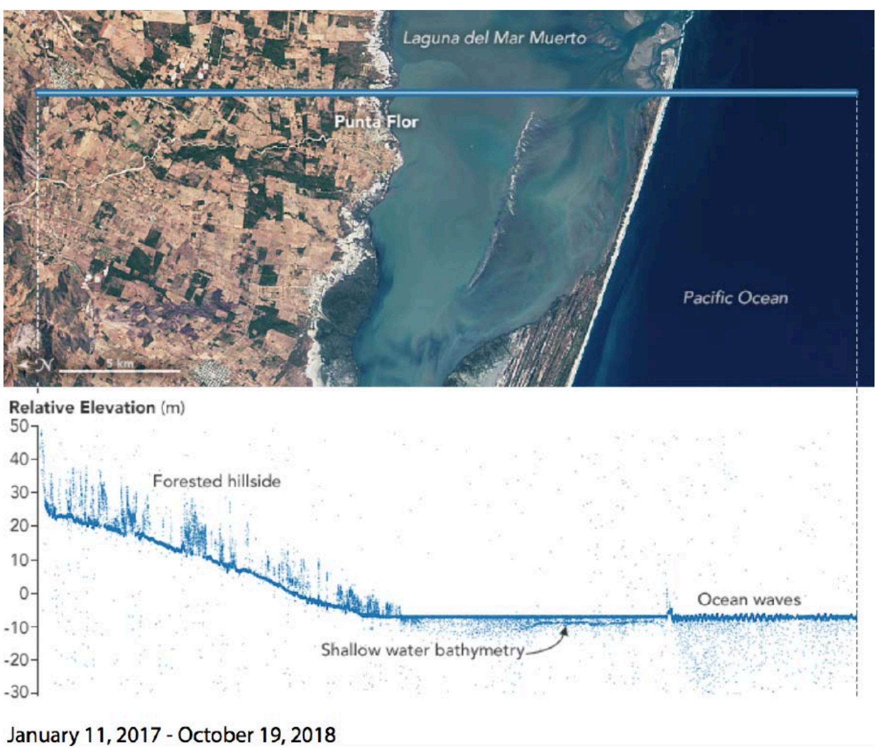
The new year got off to a challenging start for many of us when much of the U.S. Government—including NASA—shut down from December 23, 2018 to January 25, 2019. Fortunately, *The Earth Observer* contractor staff was able to continue working. While the specific plans for this issue had to be tweaked and the production schedule inevitably slipped, the publication before you is a testament to the resiliency of the team. For hardcopy subscribers to the newsletter, the previous issue of the newsletter (November–December 2018) likely only recently found its way to your mailbox due to furlough-induced printing delays.

The previous issue of *The Earth Observer* included a status update on the Ice, Cloud, and land Elevation Satellite–2 (ICESat-2) that included an image of ATLAS (lidar) returns during an Antarctica overpass.[1] But as its name implies, the mission's capabilities extend beyond studying the cryosphere. As ICESat-2 orbits over forests, it can distinguish not only the tops of trees but also the inner canopies and the forest floor—see **Figure**. While the science team was unsure how clear the terrain would be under dense canopies like those found in tropical rainforests, the data turned out even better than expected. By measuring tree heights globally, the ICESat-2 mission will be able to improve estimates of how much carbon is stored in forests.

There is also personnel news to report for ICESat-2. **Tom Neumann** [GSFC] has been named ICESat-2 Project Scientist, replacing **Thorsten Markus** [GSFC] who served in that role for the past decade. Neumann, who had previously been ICESat-2's Deputy Project Scientist, became the mission's Project Scientist after the satellite was commissioned. He has been at NASA since 2008, and was previously an assistant professor at the University of Vermont, Burlington. Neumann has conducted field work on the Greenland and Antarctic ice sheets—leading four expeditions and participating in an additional five. **Nathan Kurtz** [GSFC] has been named the new ICESat-2 Deputy Project

[1] This and several other items mentioned in this Editorial were discussed in the Editorial of the November–December 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 6**, pp. 1-3].

continued on page 2



NASA's Ice, Cloud and land Elevation Satellite-2 (ICESat-2) not only provides new data to scientists on Earth's polar ice, it also collects detailed elevation measurements over tropical and temperate latitudes, providing a remarkable look at the heights of land and ocean features.

A forested hillside in Mexico is visible in the elevation measurement [graph, *below*], acquired on October 19, 2018, by the Advanced Topographic Laser Altimeter System (ATLAS) on ICESat-2. For reference, the orbital path is laid over a natural-color image acquired on January 11, 2017, by the Operational Land Imager (OLI) on Landsat 8. Each dot on the visualization represents a photon detected by ATLAS. Most of the dots in this *photon cloud* are clustered around a surface, whether it be a tree top, the ground, or waves in the ocean. Following this orbital path from north to south [*left to right*] reveals a vegetated hillside sloping down toward the coastline. ICESat-2 can distinguish not only the tops of trees but also the inner canopies and the forest floor. As the path continues past the coastline, photons returned from the seafloor become visible. Bathymetry measurements like this are possible in clear coastal areas—sometimes as deep as 80 ft (25 m). Finally, as the path moves beyond Laguna del Mar Muerto and over the Pacific Ocean, the surface of the water is visibly rougher and the photons trace the height of individual waves.

Image and text credit: NASA's Earth Observatory

In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive.*

Scientist. Congratulations and best wishes to Neumann and Kurtz in their new roles and well-deserved thanks to Markus for helping to guide the ICESat-2 mission during his tenure.

The last issue reported on the successful launch of GEDI on December 5, 2018, and the subsequent installation of the instrument on the Japanese Experiment Module-Exposed Facility on the International Space Station on December 13. Commissioning began on January 2, 2019 and should be completed by the end of March. As of this writing, all GEDI subsystems are powered up, except the pointing control mechanism (which begins testing soon). All eight laser beams are returning waveforms. Laser pulses are consistent with pre-launch performance, and noise performance is good in all channels. Laser boresight alignment for all three lasers are good and well within field of view. Once out of the commissioning phase, GEDI will begin collecting planned science data. These early data will be used to refine science calibration efforts leading to operational production of GEDI data products.

Meanwhile, ECOSTRESS has resumed nominal operations after addressing an issue with one of its mass storage units that required switching to a redundant system (reported in the last issue). Acquisition times and revisit frequencies vary with the ISS orbit, with an average revisit over the U.S. of approximately four days. ECOSTRESS provides the opportunity to evaluate the way plants respond to heat and water stress at resolutions better than currently available sensors. ECOSTRESS data are available through the early adopter program.[2]

[2] Learn more about the ECOSTRESS Early Adopter Program at *https://ecostress.jpl.nasa.gov/applications*.

In the last issue, we reported that the GRACE–FO mission successfully completed a switchover to a backup system after an anomaly in the primary Microwave Instrument (MWI) on one of the mission's twin spacecraft necessitated the change. Once that switchover was complete, in later October, GRACE-FO resumed in-orbit checks, which included calibrations and other system tests. The GRACE-FO team has been collecting science data since the October switchover, and transitioned into the nominal science data acquisition mission phase at the end of January 2019. The team is currently doing a detailed verification and validation of the collected science data and is preparing to release the first batch in late spring 2019.

The first joint GRACE and GRACE-FO Science Team Meeting (GSTM) took place October 9-11, 2018, at GFZ, in Potsdam, Germany. The STM was an opportunity to showcase novel science applications of GRACE data. There was a particular focus on the utility of combining gravity data with data from other sensors to achieve improvements in resolving geophysical signals on improved temporal and spatial scales. These new products have already shown great potential for science and applications use, providing scientists and decision makers a new perspective on water resources. With this being the first gathering of the science team since the GRACE-FO launch in May 2018, the meeting was also an opportunity to show how these new research areas are continuing to expand. Turn to page 17 to read a summary of this meeting.

Additionally, the joint MODIS–VIIRS Science Team Meeting (STM) took place October 15-18, 2018, in Silver Spring, MD. Plenary sessions focused on overall product status (data continuity between the sensors in particular) and science investigations across the

Atmosphere, Land, and Ocean science disciplines. Each discipline had separate breakouts to discuss issues of specific interest. At the end of the STM, a Calibration Workshop was held to review the operation and measurement performance of each instrument. This science team is part of a broader effort within NASA's Earth Science Division to establish product and science continuity between EOS-era and Suomi NPP/JPSS-era observations. To read summaries of both the MODIS–VIIRS STM and the Calibration Workshop, turn to page 7 of this issue.

To close out 2018, NASA's Science Communications Support Office (SCSO) supported the NASA Science exhibit at the AGU's Fall Meeting, held December 10-14, 2018, in Washington, DC. The booth featured NASA's Hyperwall, a virtual reality space, a hands-on demonstration area, and a NASA Anniversaries area to celebrate the sixtieth anniversary of the agency. New this year, NASA partnered with AGU to successfully recruit 70 NASA scientists to participate in the AGU Centennial Narratives Project. To learn more about the exhibit and NASA's participation in the AGU Centennial Narratives Project, turn to page 4 of this issue.

Last, but certainly not least, the GPM mission is celebrating its fifth anniversary on February 27, 2019. It has provided unprecedented three-dimensional views of precipitation, from light rain to intense thunderstorms. Building on the 17-year success of the NASA–JAXA TRMM mission, the GPM Core Observatory (GPM-CO) is the first NASA satellite mission specifically designed with sensors to observe the structure and intensities of light to heavy rain and falling snow. GPM-CO includes the NASA-provided GPM Microwave Imager (GMI) and the JAXA-provided Dual-frequency Precipitation Radar (DPR). These sensors were devised as reference standards to unify precipitation measurements from partner satellite data and provide high-quality active and passive microwave observations across all times of day. These intercalibrated partner satellite retrievals are used in combination with infrared data to produce high temporal and spatial resolution of rainfall estimates every 30 minutes at 0.1° (10 km) resolution globally.

The GPM-CO mission is in extended operations with all instruments working nominally and with fuel to continue operations potentially into the early to mid-2030's. Many advances have been made with GPM data over the past five years, including improving sensor calibration, assimilation of GPM into global modeling and analysis systems, extension of latent heating products to middle/high latitudes, retrieval algorithms, and increasing understanding of the characteristics of liquid and frozen precipitation. Visit GPM on Twitter at *@NASARain* to learn more about GPM's anniversary and see other highlights from its five years of service.

I congratulate the entire GPM Team—past and present—for the success of the mission to date, and look forward to many more years of pioneering precipitation science. ■

Undefined Acronyms Used in Editorial and Table of Contents

AGU	American Geophysical Union
ATLAS	Advanced Topographic Laser Altimeter System
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
EOS	Earth Observing System
GEDI	Global Ecosystem Dynamics Investigation
GFZ	Geoforschungszentrum [German Research Center for Geosciences]
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GSFC	NASA's Goddard Space Flight Center
JAXA	Japan Aerospace Exploration Agency
JPSS	Joint Polar Satellite System
MODIS	Moderate Resolution Imaging Spectroradiometer
NOAA	National Oceanic and Atmospheric Administration
Suomi NPP	Suomi National Polar-orbiting Partnership
TRMM	Tropical Rainfall Measuring Mission
VIIRS	Visible Infrared Imaging Radiometer Suite

NASA's Outreach Activities at the 2018 AGU Fall Meeting in Our Nation's Capital

Heather Hanson, NASA's Goddard Space Flight Center/Global Science and Technology, Inc., heather.h.hanson@nasa.gov

Introduction

To close out 2018, NASA's Science Communications Support Office (SCSO)[1] supported the largest Earth and space science meeting in the world—the American Geophysical Union (AGU) Fall Meeting, held December 10-14, 2018. For nearly 50 years, the AGU Fall Meeting has been held at the Moscone Center in San Francisco, CA; however, due to the Center's renovation activities, AGU chose an alternative meeting location for both 2017 and 2018.[2] So, the 2018 Fall Meeting was held in Washington, DC.[3] To view photos from AGU and other events supported by NASA's SCSO, visit *https://www.flickr.com/photos/eospso/albums*.

Prior to the AGU Fall meeting, the SCSO organized the 2018 Annual Science Mission Directorate (SMD) Communications Meeting, where NASA employees and contractors who contribute to the agency's communications activities convened to shape outreach communications strategies and guide the workflow for the coming year—see the section, *Annual SMD Communications Meeting,* on page 6.

New this year, NASA partnered with AGU to successfully recruit 70 NASA scientists to participate in the AGU Centennial Narratives Project—see the text box, *NASA Participates in AGU Centennial Narratives Project*, on page 6.

AGU Fall Meeting

As has been the case for more than 11 years, SCSO staff organized and supported the NASA exhibit at the AGU Fall Meeting—the SCSO's biggest event of the year in terms of event support. With help from the NASA outreach community, the 70- x 50-ft (21- x 15-m) booth space—the largest NASA exhibit at AGU ever—represented the depth and breadth of NASA's science activities across SMD's four disciplines: Earth Science, Planetary Science, Heliophysics, and Astrophysics. The booth featured NASA's Hyperwall,[4] a virtual reality space, a hands-on demonstration area, and a NASA Anniversaries area to celebrate the sixtieth anniversary of the agency. Given this year's new meeting location, a large NASA Science monument—inspired by the Washington Monument—was at the heart of the exhibit—see **Photo 1**—with Washington-inspired

[1] The SCSO is the primary point of contact for NASA's Science Mission Directorate (SMD) and Earth Science Division (ESD) for science exhibit outreach and product development.

[2] The AGU diaspora gathered in New Orleans in 2017. See "NASA's Outreach Activities at AGU" in the January–February 2018 issue of *The Earth Observer* [**Volume 30**, **Issue 1**, pp. 5-8—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Jan_Feb_2018_color508_0.pdf#page=5*].

[3] AGU's Centennial is taking place in 2019; plans call for a return to San Francisco, CA to celebrate in the expanded and improved Moscone Center, December 9-13, 2019.

[4] NASA's Hyperwall is a video wall capable of displaying multiple high-definition data visualizations and/or images simultaneously across an arrangement of screens.

Photo 1. Hyperwall presenters attracted large crowds to the NASA exhibit by telling their science stories and showing dynamic visualizations. NASA's Science monument, located at the center of the NASA exhibit, can be seen near the center of this photo. **Photo credit:** NASA

street signs to help visitors navigate the exhibit. A total of 105 *science stories* (15 minutes each) and *flash talks* (7 minutes each) were offered in front of the Hyperwall, as well as 32 hands-on or virtual-reality experiences in the demonstration areas. To view the full schedule of events at the booth, visit *https://eospso.gsfc.nasa.gov/sites/default/files/publications/AGU_2018_Events_Program.pdf*.

NASA Administrator **Jim Bridenstine** and **Thomas Zurbuchen** [NASA Headquarters—*Associate Administrator of SMD*] visited the exhibit on Tuesday, December 11—see **Photos 2-3**. The two toured the exhibit and talked with several NASA booth participants before making their way to the Hyperwall stage to say a few words and introduce the winners of the *2018 AGU Data Visualization and Storytelling Competition*—a contest (funded by a grant from NASA) open to undergraduate and graduate students that focuses on innovation and creativity in presenting data to a larger audience in new, more easily accessible ways.

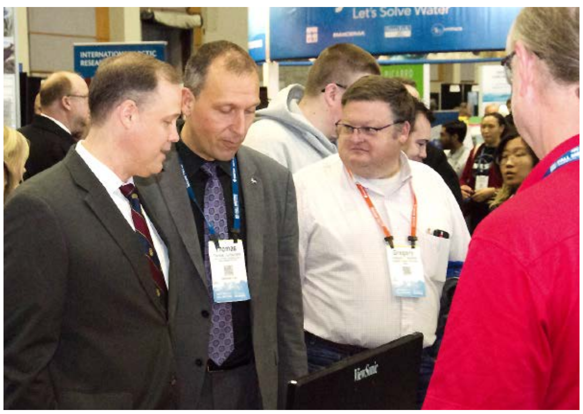


Photo 2. NASA Administrator **Jim Bridenstine** [*left*] and **Thomas Zurbuchen** [*center*] stopped at several of the activities during their tour of the NASA exhibit. **Photo credit:** NASA

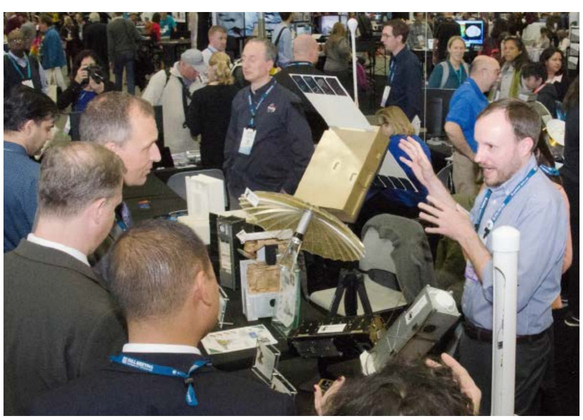


Photo 3. Philip Larkin [NASA's Goddard Space Flight Center (GSFC)] from NASA's Earth Science Technology Office talked with NASA Administrator **Jim Bridenstine** and **Thomas Zurbuchen** about NASA's latest technology discoveries. **Photo credit:** NASA

Presentations and demonstrations continuously attracted large crowds and generated lots of questions and healthy discussions among attendees. Several information tables where attendees could collect resources and talk one-on-one with NASA personnel about specific topics also received a steady stream of visitors—see **Photos 4-5**. As always, the 2019 NASA Science Calendar was one of the many resources that attracted attendees to the NASA booth—see **Photo 6**. To view the calendar online, visit *https://eospso.gsfc.nasa.gov/sites/default/files/publications/2019%20NASA%20Science%20Calendar_final_508.pdf*.

Photo 4. Attendees visiting the Landsat table learned from **Allison Nussbaum** [GSFC—*Intern*] about the long heritage of the mission and what the satellite program has allowed us to discover over the more than 40 years of the Landsat Program. **Photo credit:** NASA

Photo 5. At the virtual-reality area attendees had an opportunity to visualize NASA Science data using virtual-reality goggles. **Photo credit:** NASA

Photo 6. Attendees waited patiently to obtain a coveted copy of the 2019 NASA Science calendar. **Photo credit:** NASA

In addition to the calendar, the exhibit offered a wide range of printed materials—mission brochures, story booklets, fact sheets, and lithographs—that represent NASA's Earth Science, Planetary Science, Heliophysics, and Astrophysics activities.

New this year, the exhibit featured a hands-on activity to celebrate NASA's sixtieth anniversary called *Stepping through Moments in NASA History*. To participate, attendees were asked to take one of 5 quizzes, each with 12 questions based on the Agency's sixtieth anniversary as well as the first Apollo moon landing's fiftieth anniversary—see **Photo 7**. A small prize was given to individuals who got seven or more correct answers. The intent of this activity was to engage individuals and jog memories of NASA from 60 years ago to today.

Photo 7. NASA's *Stepping Through Moments in NASA History* activity promoted attendees to recall NASA events from the past 60 years. **Photo credit:** NASA

NASA Participates in AGU Centennial Narratives Project

The year 2019 marks AGU's Centennial year, a milestone representing the innovations, discoveries, connections, and solutions in Earth and space science over the past century, and the progress to come.

The AGU Centennial Narratives Project is an opportunity for individuals to share their personal Earth and space science stories. To support this effort, NASA successfully recruited 70 NASA scientists to participate in the project. During the AGU Fall Meeting, a team from StoryCorps* recorded longer-form interviews with the NASA participants. NASA was honored to be part of such a tremendous effort to amplify the accomplishments of science over the last 100 years.

A library of all AGU narratives will be continually updated as content is uploaded at *https://centennial.agu.org/earth-space-science-history/agu-narratives-library*.

* StoryCorps is an organization with a mission to preserve and share humanity's stories in order to build connections between people and create a more just and compassionate world. See *https://storycorps.org/about* to learn more.

Annual SMD Communications Meeting

The 2018 Annual SMD Communications Meeting was held at the Gaylord National Resort and Convention Center (located just outside Washington, DC) on Sunday, December 9. More than 180 NASA employees and contractors attended the daylong event. This annual meeting is an opportunity for those involved in NASA's communications activities, who are gathering to participate in AGU, to have a face-to-face meeting to shape outreach communications strategies and guide work flow for the coming year.

Kristen Erickson [NASA Headquarters (HQ)—*Director of Science Engagement and Partnerships*] provided opening remarks and a welcome message and introduced **Thomas Zurbuchen**, who shared his vision of the state of SMD and the agency's communication strategies. Next, the five SMD division heads—**Michael Freilich** [NASA HQ—*Director of the Earth Science Division*], **Nicola Fox** [NASA HQ—*Director of the Heliophysics Science Division*], **Lori Glaze** [NASA HQ—*Acting Director of the Planetary Science Division*], **Paul Hertz** [NASA HQ—*Director of the Astrophysics Science Division*], and **John Lee** [NASA HQ—*Director of the Joint Agency Satellite Division*]—spoke about the state of their respective SMD programs. In addition, **Dwayne Brown** [NASA HQ—*Senior Communications Official*] and **Emily Furfaro** [NASA HQ—*Social Media Specialist*] spoke about the agency's communications and social media efforts as well as future plans. In the afternoon, there were breakout sessions for the Astrophysics, Heliophysics, Earth Science, and Planetary Science Division's activities, where participants discussed story ideas and toolkit topics.

Conclusion

The SCSO plans to represent NASA at a variety of scientific venues and public events in the coming year, including the 2019 AGU upon its return to San Francisco, CA. Outreach exhibits allow the agency to represent its science activities in a single setting, often reaching thousands of people in a very short time. Currently, the Hyperwall and Dynamic Planet[5] provide exciting tools for NASA to communicate its science activities on a one-on-one basis.

Looking ahead, the SCSO remains committed to developing and implementing the next-generation communication platforms. To see where we're headed next, follow the SCSO on Twitter using @NASAHyperwall. We encourage you to stop by our displays at future venues. ■

[5] NASA's Dynamic Planet is a 48-inch spherical display system that provides a unique and vibrant global perspective of Earth, our Sun, various planetary bodies in our solar system, and the Universe, to increase and improve scientific understanding.

The Continuity Quest Continues: Summary of the 2018 MODIS–VIIRS Science Team Meeting

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Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS)–Visible Infrared Imaging Radiometer Suite (VIIRS) Science Team Meeting (STM) took place October 15-18, 2018, in Silver Spring, MD. Previous meetings of this combined imager group took place in May 2015[1] and June 2016. The focus of the team is on establishing continuity between NASA's Earth Observing System (EOS)-era MODIS products and those from VIIRS onboard the Suomi National Polar-orbiting Partnership (Suomi NPP)[2] and National Oceanic and Atmospheric Administration's (NOAA) Joint Polar-orbiting Satellite System (JPSS)-era platforms, as well as on related science.

In the four years since May 2015, much progress has been made toward this goal. MODIS is now firmly established as a high-quality science instrument with nearly two decades of continuous observations—and over thirty years of observations between Terra and Aqua, combined. Meanwhile, NASA has funded algorithm development for VIIRS (so far, for Suomi NPP only). Extensive validation efforts in the seven years since the Suomi NPP launch have shown that—despite not being specifically designed for climate science—VIIRS *can* be a worthy successor to MODIS. However, more work is needed in order for VIIRS to fulfill its full potential as heir to MODIS—the "EOS workhorse." To obtain the multidecadal time series of key environmental parameters required for climate observations, scientists on both teams have undertaken an effort to transition from products obtained by MODIS to similar products from VIIRS, wherever such comparisons are possible despite some spectral differences of the sensors. Even for two science-quality instruments such as MODIS and VIIRS, these kinds of transitions present challenges: It is never as simple as one-to-one mapping.

Probably the issue that has presented the greatest overall challenge when transitioning from MODIS to VIIRS is that VIIRS was originally designed to serve the needs of operational agencies (the National Weather Service and Department of Defense) whereas MODIS was designed to meet the needs of a global Earth and climate science/research agency (NASA). Thus, unlike MODIS, there were no formal data product continuity requirements that VIIRS was required to meet, which means it is not always easy—or even possible—to map an algorithm or data product for MODIS directly to its "equivalent" on VIIRS. This has resulted in a situation where certain EOS continuity data products cannot be produced from VIIRS for several reasons, including the lack of spectral capability from VIIRS to MODIS. In addition, this has led to several *orphaned products*, where either a proposal was not received by the agency for a given data product, or the principal investigator (PI) of an existing MODIS product or algorithm had a proposal that did not review well enough to receive funding to continue that product for Suomi NPP. This topic, as well as other challenges to MODIS–VIIRS data product continuity, were frequent topics of conversation at the meeting.

The three-and-a-half-day meeting agenda included programmatic updates from representatives of NASA Headquarters (HQ) on the overall Earth Science Program, and then on MODIS and VIIRS specifically; reports on the status of the MODIS and VIIRS

[1] The last meeting reported in *The Earth Observer* was for the 2015 meeting, see "Continuity Assured: The First Postlaunch MODIS/VIIRS Science Team Meeting Summary" in the September–October 2015 issue [**Volume 27**, **Issue 5**, pp. 12-18, 39—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/Sep_Oct_2015_color_508.pdf#page=12*].

[2] Suomi NPP, launched in 2011, was developed as a bridge mission between EOS and JPSS.

Pictured here are several members of the current MODIS–VIIRS Science Team (ST) who were also members or associates of the original MODIS ST, which first met in 1989. They include [*left to right*] **Chris Justice**, **Steve Running**, **Jan–Peter Muller**, **Michael King** [current MODIS ST Leader], **Vince Salomonson** [former MODIS ST Leader], **Bob Murphy** [former MODIS Project Scientist], and **Bruce Guenther** [former MODIS Calibration Support Team Leader]. All these individuals have been instrumental in the long-term success of MODIS on Terra and Aqua. **Photo credit:** Alan Ward instruments and their respective data products; and several sessions that were used to review algorithm development and science investigations in the Atmosphere, Land, and Ocean Disciplines. There were also opportunities for discipline-specific discussion for Atmosphere and Land,[3] including how to overcome remaining challenges in transitioning from MODIS to VIIRS.

After the STM ended, there was a MODIS Calibration Workshop held on the afternoon of October 18 and a VIIRS Calibration Workshop held the morning of October 19, which focused on the operation and measurement performance of each instrument. To learn more, see *Summary of the MODIS–VIIRS Calibration Workshop*, below.

[3] Note that, for reasons that are explained in the introduction to the *Ocean* session on page 14, the Ocean Discipline chose not to have a separate Breakout Session at this meeting.

The agenda for the week (i.e., the STM and calibration workshops), presentations, and posters can be accessed online at *https://modis.gsfc.nasa.gov/sci_team/meetings/201810*. In addition, a more detailed "white paper" summary of this meeting is posted at *https://modis.gsfc.nasa.gov/sci_team/meetings/201810/MODIS-VIIRS_STM_white_paper_final.pdf*, and is referred to throughout this article.

Day One

The first day featured an Opening Plenary Session in the morning, followed by a session on data products for MODIS and VIIRS early in the afternoon. Later in the afternoon, the focus narrowed to presentations and discussions for the Atmosphere Discipline, with emphasis on science analysis and results.

Summary of the MODIS–VIIRS Calibration Workshop

As a supplement to the MODIS–VIIRS STM, a Calibration Workshop was held in the afternoon of October 18 and the morning of October 19, focusing specifically on the calibration and characterization of the Terra and Aqua MODIS and the Suomi NPP and NOAA-20 VIIRS instruments, respectively. **Jack Xiong** and **Jim Butler** [both from GSFC] chaired the workshop, which included presentations from both the MODIS and VIIRS Characterization Support Teams (MCST/VCST) and from Atmosphere, Land, and Ocean Discipline representatives to the MODIS–VIIRS STM.

The first half-day session focused on the MODIS instruments, with presentations given by members of the MCST. These presentations outlined recent MODIS instrument performance and illustrated detailed results based on various on-orbit calibration activities. In addition, team members presented results from their investigations into improvements to calibration algorithms and mitigation of on-orbit issues. The MCST continues to calibrate and correct for the effects of aging instruments (almost 19 [in Oct 2018] and over 16 years for Terra and Aqua MODIS, respectively). The MODIS reflective solar band (RSB) gain performance has been relatively stable since the last STM in 2016. Recent improvements to the calibration include updating Aqua MODIS bands 1-4 response versus scan angle (RVS) using the response trending from both the on-board calibrators and the pseudo-invariant desert sites over a wide range of scan angles. The thermal emissive bands (TEB) have also shown excellent performance in recent years. Considerable effort was made to update the calibration of several longwave infrared (IR) bands that suffered from electronic crosstalk contamination from neighboring detectors, which affected Terra MODIS bands 27-30. The correction led to a new collection of data products, termed Collection 6.1.

The second half-day session focused on the VIIRS instruments, with presentations given by members of the VCST. Performance updates for and calibration insights into both Suomi NPP and NOAA-20 VIIRS were presented. With a few exceptions, the overall VIIRS instrument performance is more stable than MODIS.

Throughout the calibration workshop, several Science Team members presented their findings as they relate to the calibration efforts regarding these instruments. Two of the presentations covered various lunar calibration topics. Findings from presentations on cross-calibration between MODIS and VIIRS instruments demonstrated the effort needed to enable their calibration consistency. Also reported at the workshop was a brief overview of the performance of the VIIRS instrument for JPSS-2 (scheduled to launch in 2022), based on its prelaunch calibration and characterization. The direct interaction between science team members and the characterization support teams allowed multiple focus areas to be identified and discussed for improving MODIS and VIIRS science data products.

To see the full workshop agenda and download presentations, visit *https://modis.gsfc.nasa.gov/sci_team/meetings/201810/calibration.php*.

Opening Session

Michael King [University of Colorado—*MODIS Science Team Lead*] opened the meeting by welcoming the participants and reviewing the agenda.

Sandra Cauffman [NASA Headquarters (HQ)—*Deputy Director of the Earth Science Division (ESD)*] gave an opening presentation that helped place the activities of MODIS and VIIRS in the broader context of NASA's Earth Science Program. She provided an overview of the program, including an update on the status of ESD FY18 and FY19 appropriations. She noted that funding is substantial and is expected to remain at a high level for FY19 and beyond. Cauffman briefly discussed NASA Earth Science missions planned through 2023, and mentioned recent and upcoming flight program events, and Earth Venture selections.

Cauffman then provided an overview of NASA's Earth Observations from Private Sector Small Constellation Satellite Data Product Pilot project. She explained that NASA has entered into contracts with three private companies (Planet, DigitalGlobe, and Spire) to buy existing data products related to *essential climate variables* (ECVs),[4] derived from private-sector-funded small-satellite constellations. NASA researchers will determine the value of these products for advancing NASA research and applications objectives and activities. She added that NASA has identified a broad set of ESD-funded researchers who will assess the potential of the purchased information to advance NASA research and applications objectives. Cauffman also spoke about the importance of NASA's Earth Science partnerships, which currently include Google, Mercy Corps, Microsoft, and Conservation International. These partnerships allow NASA to amplify our work to understand the Earth as an integrated system and enable societal benefit. In closing, Cauffman provided a snapshot of the 2017 Earth Science Decadal Survey,[5] noting that the report identifies the key questions and challenges for Earth System Science, provides emphasis on competition as a cost-control method, explicitly allows implementation flexibility, explicitly encourages international partnerships, and endorses existing balances in the ESD portfolio.

Following up on Cauffman's opening overview, **Paula Bontempi** [NASA HQ—*MODIS* and *Suomi NPP Program Scientist*] discussed the NASA HQ perspective on MODIS and Suomi NPP. She provided an overview of the proposals received for the 2017 Earth Science Senior Review[6] on MODIS data maintenance for both Terra and Aqua (henceforth referred to as MODIS Maintenance). There were 21 proposals received for Terra and 26 received for Aqua.

Bontempi then discussed the details of the most recent Terra/Aqua/Suomi-NPP ROSES (TASNPP) call.[7] She showed a list of the EOS standard land data products recommended for Suomi NPP, ocean products for Suomi NPP, atmosphere data products recommended for Suomi NPP (some of which come from MODIS, and others from the Microwave Limb Sounder [MLS] and Ozone Monitoring Instrument [OMI] instruments on Aura), and sounder data products recommended for Suomi NPP.

Bontempi went on to address the issue of orphaned data products (described in the Introduction), distinctions between standard data products and operational data products, and algorithmic refinements (and the requirement to develop suitable documentation for each). She also noted that proposers must address work with NASA's Earth Science Data System Program and Earth Science Data and Information System (ESDIS) Project to develop accurate production and archival sizing estimates based on the nature of their products.

Bontempi cautioned that while algorithm refinements for standard products are important, in order to satisfy NASA program management and better serve the research community, the science team also needs to establish a new set of product documentation for the current standard product suite of MODIS and VIIRS, and maintain that level of documentation going forward. Lastly, Bontempi provided a list of topics for further discussion at this meeting, which became a frequent point of reference in the discussions that followed over the next several days.

Following Bontempi's presentation, the meeting's focus shifted from programmatic overviews to specific issues related to MODIS and VIIRS operations and calibration, with an emphasis on establishing continuity between the two instruments.

Xiaoxiong "Jack" Xiong [NASA's Goddard Space Flight Center (GSFC)] shared status updates on Terra and Aqua MODIS instruments and on the Suomi–NPP and

[4] ECVs derive from Climate Data Records (CDRs), which are time-series observational data of sufficient length, consistency, and continuity to record effects of climate change. Examples of CDRs include calibrated radiances, surface reflectance, and surface temperature.

[5] To learn more, see *Thriving on a Changing Planet: A Decadal Strategy for Earth Observations from Space*, which can be viewed and downloaded from *https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

[6] Historically, every two years (since 2007) NASA's Earth Science Division has conducted a review of its missions that are in *extended operations*—meaning they have completed their specified prime mission—to assess their operating status, success in achieving mission goals, and merit for continued operation. Moving forward, such reviews will be taking place every three years.

[7] This refers to Research Opportunities in Space and Earth Science (ROSES) program element *A.37*: The Science of Terra, Aqua, and Suomi NPP.

NOAA-20 VIIRS instruments. He reported that the MODIS instruments on both Terra (nearly 19 years after launch) and Aqua (more than 16 years after launch) and their onboard calibrators (OBCs) continue to operate and function nominally. Likewise, both Suomi NPP (~7 years after launch) and NOAA-20 (~1 year after launch) VIIRS and their OBCs continue to operate and function nominally. He stated that challenging issues identified for both MODIS and VIIRS will be investigated and addressed for future calibration improvements in support of their data processing/reprocessing. He also added that more efforts are needed to better understand the calibration differences among sensors (Suomi NPP and NOAA-20 VIIRS; and Aqua MODIS) and to help generate consistent data products of high quality. The Calibration Workshop provided an opportunity to delve deeper into the topics Xiong summarized in this presentation.

Kerry Meyer [GSFC] summarized the Atmosphere Discipline's Cloud Team's assessment of relative differences in shortwave radiometry between Suomi NPP VIIRS and Aqua MODIS. He noted that long-term climate data records require merging the observational records of multiple instruments (e.g., MODIS and VIIRS), and that for geophysical product continuity between sensors, relative radiometry (and radiometric stability) is particularly fundamental to the Cloud Team's physical retrievals. He pointed out that it is much more challenging for solar channels, where the absolute reflectance specifications can be greater than the expected climate change signals, and that for cloud optical properties, relative radiometric offsets (even those within specified instrument uncertainties) can induce large nonlinear intersensor retrieval differences. Then Meyer discussed a plan of action, being used by the Cloud and Aerosol Algorithm Teams, that adds radiometric adjustment factors into the L2 code to reconcile radiometric-induced retrieval differences.

Bryan Baum [Science and Technology Corp. (STC)—*Suomi NPP Team Leader*] provided his perspective on achieving continuity from MODIS to VIIRS. He demonstrated the ability to construct infrared (IR) radiances for imagers based on imager–sounder data fusion, most recently the construction of Aqua MODIS-like channels for VIIRS. This methodology has been expanded to AVHRR/IASI and AVHRR/HIRS.[8] He also stressed the importance of moving from *instrument teams*, which were common 20 years ago, to *measurement teams*—because scientists need data continuity datasets that extend beyond the lifetime of a single instrument. The priority of the Terra/Aqua/Suomi NPP program is to achieve the best product continuity possible; this may necessitate use of ancillary data from other polar-orbiting and geostationary (GEO) sensors.

Chris Barnet [STS—*Suomi NPP Sounder Team Leader*] discussed the Community Long-term Infrared Microwave Coupled Atmospheric Product System (CLIMCAPS). CLIMCAPS is a NASA continuity product system that is based on the NOAA-Unique Combined Atmospheric Processing System (NUCAPS) and the use of AIRS/AMSU (on Aqua) and CrIS/ATMS (on Suomi NPP and NOAA-20) continuity products for cloud feedback studies.[9] CLIMCAPS uses the NASA GEOS-5[10] product for retrieval initialization. He described the work that has been done to create a hyperspectral sounding continuity product and showed examples of retrieval products that meet the needs of three communities: weather (e.g., extreme events), climate (e.g., processes, long-term trends), and composition (e.g., trace gases and air quality). He stated that NUCAPS is supporting real-time-weather and air-quality applications, and that the NASA continuity product will focus on developing a long-term (2002–2040) record for AIRS/AMSU and CrIS/ATMS. He concluded by stating that CLIMCAPS is designed to support community needs, asking participants how CLIMCAPS could support their research.

MODIS/VIIRS Aerosol Algorithms Status and Atmosphere Discipline Science

Steve Platnick [GSFC—*MODIS Atmosphere Discipline Leader*] chaired this session. These presentations focused on determining aerosol optical properties and science using MODIS and/or VIIRS. They addressed topics that ranged from aerosol-related algorithm development to application of the resulting data products. (See Table 1 in the white paper at the URL referenced earlier for details.)

MODIS/VIIRS Cloud Algorithm Status and Atmosphere Discipline Science

Steve Ackerman [University of Wisconsin–Madison—*VIIRS Atmosphere Discipline Leader*] chaired this session, covering cloud algorithms and a variety of science topics related to the Atmosphere Discipline. The presentations described topics that ranged from the characteristics and effects on other measurements of

[8] AVHRR stands for Advanced Very High Resolution Radiometer, which has flown on a series of NOAA, NASA, and international platforms since 1978; the last AVHRR launched in 2018 on the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT's) MetOp-C platform. IASI stands for Infrared Atmospheric Sounding Interferometer, which has flown on MetOp-A, -B, and -C. HIRS stands for High-resolution Infrared Radiation Sounder, which also flies on the MetOp series.

[9] AIRS stands for Advanced Infrared Sounder, and AMSU stands for Advanced Microwave Sounding Unit. CrIS stands for Cross-track Infrared Sounder, and ATMS stands for Advanced Technology Microwave Sounder.

[10] GEOS-5 stands for Goddard Earth Observing System Model, Version 5, which is run by the Global Modeling and Assimilation Office at GSFC.

several physical parameters (e.g., aerosols, ice crystals) to new approaches for detection and mapping of such phenomena. (See Table 2 in the white paper at the URL referenced earlier for details.)

Day 2

The second day of the meeting began with three more presentations related to the Atmosphere Discipline. After that the focus moved to the Land Discipline for the remainder of the morning. The afternoon was dedicated to parallel breakout sessions held by the Land and Atmosphere Disciplines.

MODIS/VIIRS Atmosphere Discipline Science (continued)

Bryan Baum was the chair of this short session. All of the presentations in this session described efforts to incorporate data and products from multiple sensors into their investigations. The scientific studies are continuing to evolve from single- to multiple-sensor data fusion efforts. (See Table 3 in the white paper at the URL referenced earlier for details.)

MODIS/VIIRS Land Science Analysis

Chris Justice [University of Maryland—*MODIS–VIIRS Land Discipline Co-Leader*] was chair of this session (and the Land Breakout Discussion that followed in the afternoon of the second day). His opening remarks for this session focused on the MODIS-to-VIIRS transition particularly as it applies to Land products, from the initiation of MODIS on EOS Terra to today. With such a continuous history, we now have the basis for a long-term and—with sophisticated reprocessing techniques—a reliable data record—essential for studying the impact of climate changes. Further, explicit quality assurance procedures have been developed and are routinely implemented at the Land Science Investigator-led Processing Systems (SIPSs).[11] He noted that the data are readily and widely accessible through a variety of means.

Justice went on to describe the relationship between MODIS and VIIRS in terms of objectives, design, and implementation—and why there are differences. Data continuity is further enhanced by noting that in many cases the VIIRS data products have been developed using the heritage algorithms from MODIS, with MODIS PIs heavily involved in the process. As Paula Bontempi showed in her remarks in the Opening Session, some MODIS products, including several land products, have been orphaned (i.e., they will not continue with VIIRS). Justice explained some of the reasons for the lack of continuity between MODIS and VIIRS, particularly in the context of Land algorithms and data products—see Introduction to this article and Justice's full presentation for more details.

Despite the continuity challenges that must be overcome, the transition between these two instruments presents an opportunity for a Research-to-Operations (RtO) transition. Opportunities often come coupled to challenges; in this case the challenge is for NASA and NOAA to figure out ways to work together for a smooth transition from RtO [i.e., from NASA MODIS (EOS) and Suomi NPP VIIRS to NOAA JPSS series, e.g., NOAA-20]. The science community already has a long-term record of coarse-resolution observations (with the previous transition from AVHRR to MODIS) but this time, with the operational VIIRS instrument also being a science-quality instrument, the transition is from one science-quality instrument to another.

Justice then reviewed the MODIS proposals related to Land, which were selected from the most recent TASNPP call. He showed a list of proposals continued from the previous selection (referring to the 2014-2017 ROSES call—*Science of Terra and Aqua*) that are undertaking new science or developing new data products under the TASNPP call. After that, he quickly ran through the ongoing projects (funded through MODIS Maintenance) that are part of the recent Senior Review and gave an update on the status of each. He encouraged participants to visit the Poster Session to learn more.

Justice ended his remarks with a summary slide of the foci for the Land Team discussions during the afternoon's breakout session. The overarching theme of all his bullet points was for the community to help develop a long-term strategy for NASA Land Products.

Miguel Román [GSFC—*MODIS–VIIRS Land Discipline Co-Leader*] followed with an overview of the Land data products from Suomi NPP. He showed a flowchart of the NASA VIIRS Land Product Interdependencies. His emphasis was on the impact that the orphaned products from the most recent TASNPP call will have on the flow of data products. He said that as much as possible, MODIS-equivalent Collection 6 products will be used to mitigate effects of orphaned products.

Román then discussed the current status of the VIIRS Land Processing SIPS for Version 1.0 of the Suomi NPP VIIRS algorithm. He also looked ahead to plans for reprocessing efforts beyond Version 1.0, and went on to show examples of VIIRS Land products in action. He emphasized the current continuity between MODIS and VIIRS, noting that several data products (e.g., active fires, cryosphere) show areas where using VIIRS data clearly improves over results obtained with MODIS. Román closed by describing validation activities for VIIRS.

[11] ESDIS supports data processing by providing SIPSs for processing EOS standard products. Most SIPSs are under the direct control of the instrument principal investigators/team leaders (PIs/TLs) or their designees, and typically collocated with the PIs/TLs.

The remainder of this session consisted of four presentations on selected VIIRS Land products, with topics ranging from algorithm improvement efforts for several products to the development of the "Black Marble" view of Earth's surface at night. (See Table 4 in the white paper at the URL referenced earlier for details.)

Discipline Breakout Sessions

The two parallel sessions summarized below took place on the afternoon of the second day of the meeting.

Atmosphere

Steve Ackerman and **Steve Platnick** facilitated the Atmosphere Breakout discussion, which intentionally emphasized open discussion over a series of presentations on specific research topics. Discussion topics focused on how to efficiently and effectively produce useful EOS–Suomi NPP/JPSS continuity data products for science team investigators and the larger community. Ackerman and Platnick began with some opening remarks to set the tone for the discussion. Ackerman reported that project summaries, as represented as two-page slides, were collected from all Atmosphere Science team PIs and will be distributed to the Atmosphere Team.[12]

At the request of the facilitators, **Kevin Murphy** [NASA HQ—*NASA Program Executive for Earth Science Data Systems*] then spoke to clarify some questions that had come up during and/or after Paula Bontempi's remarks in the Opening Plenary concerning the status of orphaned products. He explained that if a product is supported only through Senior Review MODIS Maintenance or MEaSUREs,[13] the SIPS is still tasked with production as long as the PI can support the product. This includes archiving and delivery of the data through the L1 and Atmosphere Archive and Distribution System (LAADS). On the other hand, if PIs are no longer funded, then they need to indicate that the product is no longer supported (i.e., orphaned) and that SIPS can only continue to support orphaned products until the product "breaks," e.g., if the product is not compatible with a new production system.

Liam Gumley [University of Wisconsin-Madison] gave the only formal presentation during this breakout, following up on Murphy's comments as regards orphaned atmosphere products as they apply to the Atmosphere SIPS. He then explained that the Deep Blue Aerosol (AERDB) products have been reprocessed four times in the past year, and showed an example using Worldview (defined in footnote 18 on page 14). He also showed an example of the Cloud Mask (CLDMSK) products in Worldview and demonstrated the impact of the Cloud Top and Optical Properties (CLDPROP) product by showing comparison of L3 data processing versus swath width. (For a breakdown of the Atmosphere data products, see Table 5 in the white paper at the URL referenced earlier.)

The discussion then turned to the importance of stewardship. The Atmosphere Discipline affirmed its support for the NetCDF4[14] data format for continuity products and for MODIS future collections.

Following Gumley's presentation, there was more discussion on product documentation and publications. Specifically, clarifying the definitions of and need for user guides and Algorithm Theoretical Basis Documents (ATBDs), along with the history. The consensus of the Atmosphere Team was to focus on user guides, which refer to previous ATBDs and published papers but are more directly relevant to users than traditional ATBDs. Continuity product user guides have been written and are hosted at LAADS. Science team investigators asked to provide input on the documents. Next there was discussion of the status of the products and the schedule, focusing on some continuity challenges and remaining uncertainties.

The topic of continuity challenges between MODIS and VIIRS arose again in this breakout discussion, specifically: *How do the algorithm groups plan to demonstrate that products have continuity with earlier datasets?* Discussion between algorithm developers and science investigators suggested that continuity depends on product usage. Current foci of developers include developing time series across large regions, doing pixel-level intercomparisons (to the extent possible), and using other independent methods (e.g., ground-based networks).

With regard to uncertainty, the consensus was that there is no single/simple answer or methodology to determine product uncertainty, as it depends on the part of the geophysical parameter space being observed and what datasets or combination of datasets are used. The discussion touched on several different approaches that Atmosphere Algorithm developers use.

There was also conversation about the status of L3 data products, which while not explicitly proposed in the TASNPP call—were not orphaned. After that came a discussion about how to address issues in relative calibration between VIIRS and MODIS. Long-standing questions remain, such as: *How often do we need to change coefficients? How do we keep science quality in the forward stream?* No decisions were made with regard to those questions.

[12] These summaries can be found at *https://www.ssec.wisc.edu/mvac/october-2018-meeting*. Note that some Team members had just received funding when the meeting took place, and thus did not have slides compiled.

[13] MEaSUREs stands for NASA's Making Earth Science Data Records for Use in Research Environments.

[14] NetCDF is a set of software libraries and self-describing, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data.

These questions apply to another issue that came up during the discussion: the need to add NOAA-20 (sometimes referred to as J1) to the calibration intercomparison infrastructure. This led to the broader question: *How will the SIPS continue to support calibration activities for new satellites?*

The wrap-up discussion included an Atmosphere Discipline priority to work with the new generation of GEO imagers (e.g., ABI, AHI),[15] including Aerosol Dark Targets. All algorithms have been ported and had initial (limited) testing on these GEO imager data products.

Land

Chris Justice facilitated the discussion, assisted by **Miguel Román**. Justice started by giving an overview of topics to be covered throughout the afternoon in freeform discussions and/or specific presentations. The discussion was an opportunity to formulate the MODIS–VIIRS Land Discipline's responses to Paula Bontempi's suggested topics for further discussion. Specific topics (which are elaborated on in the description that follows) included:

- Discussion of the status of MODIS Collections 6 and 6.1 (C6 and C6.1);
- discussion of VIIRS delivery and related issues;
- discussion of Land Processes Distributed Active Archive Center (LP.DAAC) and National Snow and Ice Data Center (NSIDC) data product distribution status and product use;
- discussion of VIIRS and Sentinel-3 Surface Reflectance, and a broader conversation about the potential of having Sentinel-3 serve as a *de facto* "AM Platform" after Terra is turned off;
- discussion of Suomi NPP and NOAA-20 Land Products; and
- discussion of Land Product Synergy.

There was discussion of the status of current Land proposals and where they fit in terms of elements from the TASNPP call[16] and ensuring the Land SIPS have the information they need in terms of product integration and generation planning. There was also discussion of VIIRS Land orphaned products, and how they will be managed by Land SIPS—following the example of the Ocean Team. **Glynn Hulley** [GSFC] noted that he wants to reduce the number of land surface temperature (LST) products currently being supported.

In a reprise of the remarks he gave to the parallel Atmosphere Breakout discussion, **Kevin Murphy** gave some additional HQ direction on orphaned products that Paula Bontempi had mentioned. (See summary on page 12 for specifics.)

There was then conversation about the need for a continued science presence in quality assurance (QA) and that the SIPS has been stepping up to perform this task. The SIPS has also been increasingly involved in coding for some of the Land products. Justice inquired as to the current work load for MODIS Maintenance, given that we will now have to maintain two algorithms: MODIS and VIIRS. The question is: *At the end of this funding cycle, will VIIRS products go into Senior Review?*

Another question that came up was whether the Team is providing sufficient and useful information for users to be able to easily access and use the products. Román stressed the importance of learning more about the makeup of the Land user community, as many users are non-academics, and the learning curve to actually use the data is steep. Good user guides may be a helpful resource, particularly for new users.

Justice next reminded the participants that the Land SIPS recompete is coming up. With the prospect of international and—potentially—GEO missions, in the framework of moving from a mission/instrument-focus to a measurement-focus the questions for Land are: *Where will these data be processed, and will there be higher order products and, if so, who will take care of their stewardship?* The question was raised as to how NASA intends to implement such a *missions-to-measurements* agenda. One suggestion was that this could be a new focus for the MEaSUREs program.

Resources are being put into the MODIS Characterization Support Team (MCST) and VIIRS Characterization Support Team (VCST). Justice inquired whether their findings are getting back to the Team for the key products (e.g., surface reflectance, LST). There was also interest in understanding how the two MODIS Land calibration activities funded under the Senior Review contribute to the overall calibration efforts and the associated Land products. For Land product validation, given the limited funding, PIs are encouraged to leverage the activities of the Committee on Earth Observation Satellites (CEOS) Land Product Validation (LPV) Working Group. Justice noted that NASA continues to take a lead role in CEOS LPV activities.

Based on Paula Bontempi's opening remarks about standard data products, the group felt that reviewers need a better understanding of what it takes to develop and

[15] ABI stands for Advanced Baseline Imager, which flies on NOAA's GOES-R series (NOAA-16 and -17). AHI stands for Advanced Himawari Imager, which flies on Japan's Himawari geostationary satellites (Himawari-8 and -9).

[16] The elements were: *2.1* Sensor Fusion; *2.2* New Data Products; *2.3* Continuity Product Creation; *2.4* Near Real-Time (LANCE).

generate land products and what products the broader community see as important. The question was raised as to what land products does the community desire? This topic will be the subject of a land workshop to be held in 2019, details of which have not yet been determined.

After this conversation came four presentations on some of the remaining topics Justice outlined at the beginning. They are detailed in Table 6 in the white paper at the URL referenced earlier.

Following these presentations there was discussion on a popular topic: *Can NOAA and NASA find ways to effectively collaborate on products from the JPSS missions?* Justice suggested that it would take buy-in from management of both organizations to do this over the long-term, with an intentional framework to get us where we want to go. **Paula Bontempi** indicated "there is currently no NASA money allocated for products from the JPSS series." However, **Jim Gleason** [GSFC—*Suomi NPP Project Scientist*] felt that to the extent the PI can show our products have value for answering critical Earth Science questions, they will continue to receive funding.

Justice then led an initial discussion on a Land Product Strategy during which the group returned to the Land Team foci for this meeting that Justice had shown in his morning presentation, as discussed on page 13. During the conversation, someone asked whether rapid advances in moderate-resolution and hyperspectral imagery capabilities will eventually render relatively coarse-resolution products (e.g., MODIS and VIIRS) obsolete. Justice felt that while global scale products from Landsat/Sentinel are now feasible, we are a long way from a suite of standard time series products that would make coarse-resolution products derived from daily data obsolete.

Hank Margolis [NASA HQ—*Program Manager for Terrestrial Ecology Program*] closed out the breakout session with the HQ perspective on these various topics. He began with the obligatory NASA Science Fleet diagram, then remarked that NASA Administrator **Jim Bridenstine** has been quoted as saying, "Earth is my favorite planet," which implies how important it is to study the Earth and understand its changing climate. However, in her remarks at the beginning of the meeting, **Paula Bontempi** said that NASA program managers and proposal reviewers tend to downplay the importance of proposals discussing tweaking the details of algorithms—which are, of course, vital to continue to refine our understanding of "our favorite planet's" changing climate.

How do we close this gap between these two seemingly contradictory statements?

Margolis felt that one key to closing the gap is to continue to produce groundbreaking science. He further suggested that Team members can help with peer-review panels for proposals, where they can be a voice for the value of algorithms and other refinements. Also, when a publication is created, authors should be sure to acknowledge the support of NASA programs. Team members should also share new ideas with HQ, ideally via white papers. Margolis ended by noting that the 2017 Earth Science Decadal Survey offers intriguing possibilities, particularly for Terrestrial Ecology.

Day Three

The morning of the third day was for the remaining Land Discipline presentations. Following that, the Ocean Discipline took center stage for the remainder of the day.

MODIS–VIIRS Land Science Analysis

Chris Justice chaired this session; he noted that the presenters in this short session were some of the newly selected investigators. He also mentioned that the final presentation in this session was from a new NASA initiative—GEONEX—which is focused on generating products from GEO data. These presentations addressed topics ranging from new techniques to measure physical and biological phenomena to problems with and refinements of several models, and potentially new applications of land data products. (See Table 7 in the white paper at the URL referenced earlier for details.)

MODIS/VIIRS Ocean Algorithms and Science Analysis

Brian Franz [GSFC—*MODIS–VIIRS Ocean Discipline Co-Leader*] chaired this session. He began by mentioning that Ocean Discipline Team attendance is light due to another ocean-related meeting taking place this week.[17] Taking this into consideration, the Oceans Discipline opted *not* to have a separate Ocean Breakout at the MODIS–VIIRS STM. Franz reported that an Ocean Discipline Telecon—with complete attendance of all Ocean Discipline PIs—was held on July 16, 2018, which served as their "Breakout Session"—see *Ocean Discipline Summary Report* on page 15 for details on the content of the telecon. Given the conflict with the other meeting, the presentations from the Ocean Discipline for this year largely emphasized new work and cross-disciplinary efforts. (See Table 8 in the white paper at the URL referenced earlier for details.)

Day Four

The final morning of the meeting contained only one presentation, on the Global Imagery Browse System

[17] This was the Ocean Optics XXIV meeting held October 7-12, 2018, in Dubrovnik, Croatia.

(GIBS) and Worldview application.[18] After that, there were plenary reports from each discipline team (Land, Ocean, Atmosphere) on their deliberations over the course of the meeting, primarily focusing on the breakout discussions, followed by a closing discussion. The afternoon and Friday morning were used for the earlier-mentioned Calibration Workshops.

MODIS and VIIRS Data Access through GIBS and Worldview

Matt Cechini [Science Systems and Applications, Inc. (SSAI)] and **Ryan Boller** [GSFC] discussed the availability of MODIS and VIIRS products via the GIBS/Worldview system. Cechini began with an overview of GIBS/Worldview. He noted that 83% of tile requests are for MODIS and VIIRS imagery. Boller covered Worldview, showing a demonstration of the application's capabilities, particularly as they are applied to viewing MODIS and VIIRS imagery.

Plenary Session: MODIS and Suomi NPP Discipline Summary Reports

Land

Chris Justice began by saying that he feels the next three years will be critical for the future of land products for NASA Earth Science. A long-term goal of NASA Earth Science is the creation of Earth System Data Records—i.e., continuity. Even while the Land Team is wrestling with how to make the transition from EOS to JPSS, Justice suggested that now is the time to plan for change—but also a time to look back, assessing lessons learned from our past. He showed a photo of the MODIS Land Team from 2001, and estimated that 70% of the people in the photo are still in the room today. He paid tribute to **Vince Salomonson** [University of Utah—*Former MODIS Science Team Leader*] and all those who helped build a strong foundation for the NASA Land products and the associated science from MODIS and VIIRS. Justice closed by summarizing the content of Land breakout session discussions.

Steve Running [University of Montana] suggested having an *EOS Victory Lap* and a special session at the 2019 AGU (which is AGU's hundredth anniversary meeting), thereby providing a chance to look back on the 30 years of EOS and to plan "the next 30 years."[19] He agreed with Justice's earlier statement that the next three years are crucial in planning for the future of NASA Earth Science.

Atmosphere

Steve Ackerman explained that the Atmosphere group had only one presentation (on behalf of the Atmosphere SIPS) and that the breakout was discussion-focused. Ackerman summarized these discussions, noting the development of several action items, addressing calibration adjustment factors between MODIS and VIIRS, input on user guides, user aggregation needs, browse imager requirements, and new-generation imagers and associated algorithms.

Ocean

Bryan Franz discussed details of the Ocean Discipline Team's telecon on July 16, 2018, which served as their "Breakout Session," as described earlier. The telecon had full participation, and the agenda included programmatic business, Ocean Team overview, organizational procedures and responsibilities, and discussion of PI proposals. He also reported on the status of the Ocean proposals selected under the TASNPP call as well as the MODIS Maintenance Proposals.

Franz noted that the Ocean SIPS is currently producing all standard products for NOAA-20 VIIRS, and that they are publicly available through the ocean color website (*https://oceancolor.gsfc.nasa.gov*) as provisional L2 and L3 products. He showed a list of when each dataset (i.e., ocean color and sea surface temperature for MODIS and VIIRS, respectively) was reprocessed.

Franz then showed a list of Ocean standard products, pointing out the two orphaned products for Oceans, and then showed four possible future standard products. Similar to the Atmosphere and Land Breakout Sessions described in this article, there was more discussion at the telecon about: *When does a product become standard?* Franz showed the procedure the Ocean Discipline follows for a product to become standard.

The Ocean team also touched on another question with which all Disciplines are wrestling at the moment: *What constitutes sufficient documentation for a data product?* Franz said that an end user needs a product guide—and it needs to be kept up to date. The overwhelming consensus from all three disciplines is that, after the initial ATBD is compiled at the beginning of a mission, a user guide is preferred for updates. A user guide is more practical and, at least theoretically, kept up to date. In place of a user's guide and/or ATBD, the Ocean SIPS utilize Product and Algorithm Description Documents (PADDs), which are living documents that include a brief description of the product and its purpose; a brief description of the algorithms with links to associated publications for more details; details of implementation differences for each sensor; direct (live)

[18] Worldview is an application (which runs in GIBS) that enables interactive browsing of global satellite imagery within hours of its being acquired—*https://worldview.earthdata.nasa.gov*.

[19] Such an event was held in Washington, DC, in June 2009, to mark the twentieth anniversary of the EOS program. To read a summary, see "NASA Earth System Science at 20: A Symposium to Explore Accomplishments, Plans, and Challenges" in the September–October 2009 issue of *The Earth Observer* [**Volume 21**, **Issue 5**, pp. 18-30, 39—*https://eospso.gsfc.nasa.gov/sites/default/files/eo_pdfs/Sept_Oct09.pdf#page=18*].

links to source code for even more details; and product validation results with live links.

Franz noted that the DAACs have been working to make it easier to find documentation, and provided an example of this effort—a screenshot from the Ocean SIPS/Ocean Biology DAAC (OB.DAAC) (*https://oceancolor.gsfc.nasa.gov/product_status*), which has a table that lists links to PADDs for each product; product status (i.e., standard, provisional, test, special); links to the mission description pages; and links to digital object identifier (DOI) landing pages per product and product level.

Franz then discussed the status of support for VIIRS on NOAA-20 (a.k.a., J1). The Ocean SIPS has been funded to acquire J1/VIIRS L0 data and produce L1B, L2, and L3 continuity products. However, the MODIS–VIIRS Science Team has not been funded to support J1/VIIRS. The Ocean Science Team is trying to offer support in whatever ways it can. In particular, the Ocean Science Team is supporting generation of atmospheric correction look-up tables and performing vicarious calibration. Furthermore the OB.DAAC is currently distributing the J1/VIIRS L1B, L2, and L3 Ocean Color products produced by the Ocean SIPS (*http://oceancolor.gsfc.nasa.gov*).

Closing Discussion and Reflections on the Way Forward for the MODIS–VIIRS STM

Michael King began a plenary-closing discussion with some reflections on the meeting. He enjoyed the history, and noted that the plenaries where we get to hear from all disciplines are especially valuable. He thought there was value in continuing to offer this kind of gathering.

King also noted that NASA HQ has asked him to prepare something to highlight "accomplishments of each instrument" for Terra's twentieth anniversary—in December 2019. **Alan Ward** [GSFC/Global Science & Technology, Inc.] mentioned that *The Earth Observer* newsletter published an article for Terra's fifteenth anniversary that listed 15 accomplishments, sorted by the 5 instruments onboard.[20]

Steve Running, another veteran of the EOS Program (Land), offered his perspective on the meeting format. He said that he actually did get inspiration for one of his investigations from an Oceans presentation at a MODIS STM. "Gee," he thought, "If sea level didn't rise, where did all that water go?" That became the impetus for research that led to a major publication.

Chris Justice mentioned that at one point, EOS Investigators Working Group (IWG) Meetings were a way to bring disciplines together. Those meetings were driven by interdisciplinary science (IDS), but they stopped happening in 2002 for a variety of reasons. He suggested that maybe something akin to an IWG Meeting could be a way to reframe these STMs to make them more effective and aligned with NASA HQ's current emphasis on shifting the focus "from missions-to-measurements."

Paula Bontempi said that she intends to take the input from these disciplinary summaries back to her colleagues at NASA Headquarters.

Taking a moment of personal privilege, Bontempi reflected that she might be one of the few people in the room today who will still be at NASA by the time the "third Decadal Survey" is conducted. She noted that we are leaving behind the "EOS era," and pointed out that our international partners, some of whom contributed instruments for EOS, have now built their own programs. She said that we are back to a pioneering era of sorts. She said that **Mike Freilich** [NASA HQ—*Director of Earth Science Division, Outgoing*] wanted to focus on Earth System Science in the second Decadal Survey. Leadership thinks "we're there" but proposals are lagging: e.g., too frequently, teams are still focusing on tweaking existing algorithms as opposed to developing something new and innovative. She asked the Team to consider: *If you had unlimited resources, what would you want to do?*

Bontempi added that, in her opinion, Decadal Surveys are open opportunities to submit white papers about what the priorities for the next generation should be. Decadal Surveys have created new methods to have missions: e.g., the Earth Venture program. Funds may not be as abundant as they once were, but she encouraged the Team to take advantage of the programs that do exist.

Conclusion

Overall, the 2018 MODIS–VIIRS STM was highly successful. It was an opportunity for the ST to engage in productive discussions on the ongoing quest for MODIS–VIIRS continuity, and to learn about the latest science results from MODIS and VIIRS across the Atmosphere, Land, and Ocean Disciplines. There were general programmatic and instrument updates as well as discipline–specific discussions about how to address barriers to continuity, e.g., instrument intercalibration, orphaned products, as well as more general issues of data provenance, accessibility, and documentation for data products.

The EOS Program is about to turn 30, and the EOS "Flagship" (Terra) will celebrate 20 years in orbit in December 2019. As we move beyond EOS into the JPSS era, the MODIS–VIIRS ST seeks to continue to play an important leadership role as it has in the past.

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[20] To learn more, see "15@15: 15 Things Terra has Taught Us in Its 15 Years" in the January–February 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 1**, pp. 4-13—*https://eospso.nasa.gov/sites/default/files/eo_pdfs/JanFeb2015_color_508.pdf#page=4*].

Summary of First Joint GRACE and GRACE Follow-On Science Team Meeting

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Introduction

After more than 15 years of operations, the Gravity Recovery and Climate Experiment (GRACE) mission recorded its last mass-change observations in June 2017, with its science mission officially ending in October 2017. A joint endeavor between NASA and the Deutsches Zentrum für Luft-und Raumfahrt (DLR) [German Aerospace Center], the twin GRACE satellites improved our understanding of Earth's dynamical nature, making precise measurements of changes in the gravity signals associated with exchange of mass between several Earth-system components.

On May 22, 2018, the continuity mission, called GRACE Follow-On (GRACE-FO) was successfully launched on a Space-X Falcon 9 launch vehicle from Vandenberg Air Force Base in California. GRACE-FO is another U.S.–German collaboration, this time between NASA and the Geoforschungszentrum (GFZ) [German Research Center for Geosciences]. The mission will continue the 15-year data record of monthly global mass changes from the first GRACE mission. While the primary mission objective of GRACE-FO is to provide continuity from the monthly mass-change observations of GRACE via its Microwave Ranging Instrument (MRI), the FO mission also carries a novel Laser-Ranging Interferometer (LRI) as a technology demonstration of more-accurate satellite-to-satellite ranging observations. Since launch, the science instruments on GRACE-FO—including the Microwave Interferometer (MWI), the accelerometer, and the experimental LRI—have been initialized, calibrated, and their performance assessed by the project's Science Data System (SDS) team.

The first joint GRACE and GRACE-FO Science Team Meeting (officially GGFOSTM, but referred to simply as GSTM henceforth in this article) took place October 9-11, 2018, at GFZ, in Potsdam, Germany. More than 120 participants—see photo below—attended the meeting, which consisted of 42 oral presentations and poster sessions distributed across the sessions, as summarized here. The complete GSTM program, abstracts, and many of the presentations are available at *https://www.gstm-2018.eu*.

The first day of the meeting was dedicated to two programmatic sessions, detailing GRACE and GRACE-FO Project status. The second and third days of the meeting featured six science sessions, with presentations that included analytical techniques for gravity mission data, methods to bridge the gap between the end of science operations for GRACE and beginning of science data collection with GRACE-FO, general discussion on how to implement next generation gravity missions,[1] as well as applications of mass transport data in the fields of hydrology, oceanography, glaciology, and solid-Earth sciences. The final session of the meeting was a discussion of GRACE and

[1] To clarify, the European Space Agency does have a mission concept they call the Next Generation Gravity Mission (*https://www.rheagroup.com/news/next-generation-gravity-mission-will-measure-earths-gravity-field-unprecedented-resolution*) but this conversation was a more general discussion about ideas for future mass change and gravity studies.

Photo of the GRACE STM participants outside the meeting facility in Potsdam, Germany. **Image credit:** Elisabeth Gantz [GFZ]

GRACE-FO applications in the broader context of NASA's Applied Science Program. In addition, posters relevant to each topic were displayed for discussion throughout the meeting.

GRACE Project Status

After host **Frank Flechtner** [GFZ—*GRACE Co-Principal Investigator* and *German GRACE-FO Project Manager*] welcomed the participants, **Byron Tapley** [University of Texas, Center for Space Research (CSR)—*GRACE Principal Investigator (PI)*] began with a formal presentation on the GRACE satellites and instrument status at the end of the mission.

The data collected by the GRACE satellites supports the generation of 163 monthly gravity field solutions (out of a maximum possible 182). Most of these monthly solutions have already been reprocessed by the SDS processing centers [at CSR, NASA/Jet Propulsion Laboratory (JPL), and GFZ] based on reprocessed Level-1B (L1B) instrument data, updated processing standards, and improved background models. Preliminary assessment of these Release-06 (RL06) monthly measurements of Earth's gravity field indicates notable improvements over the previous Release-05 (RL05) product.

Tapley highlighted that the final-stage GRACE mission activities focused on minimizing the projected gap between the GRACE mission end and the GRACE-FO launch. The extended mission science tasks are to reanalyze the 15-year dataset to obtain the final Release-07 (RL07) data record, to implement an approach for bridging the gap between the GRACE and GRACE-FO, and to archive all mission data.

Several programmatic presentations came next. **Gerhard Kruizinga** [JPL] reviewed the status of GRACE L1 reprocessing at JPL. **Henryk Dobslaw** [GFZ] summarized the status of the RL06 L1B Atmosphere and Ocean Dealiasing product (AOD1B); and **Himanshu Save** [CSR], **Christopher McCullough** and **David Wiese** [both from JPL], and **Christoph Dahle** [GFZ] reviewed the status of the latest RL06 L2 products produced by CSR, GFZ, and JPL, respectively.

GRACE-FO Project Status

This session provided an overview, assessment, and summary of the GRACE-FO mission, activities, events, and outcomes from launch and early operations (LEOP) through the in-orbit checkout (IOC) of the main science payload instruments and satellite calibrations.

Frank Webb [JPL—*GRACE-FO Project Scientist*] began with a high-level report on the current status of the GRACE-FO mission and the planned next steps. After that **Nico Brandt** [Airbus] briefed the Science Team on the satellite operating status of the GRACE-FO satellites, and **Franz-Heinrich Massman** [GFZ] reported on mission operations at the German Space Operations Center (GSOC), which is responsible for GRACE-FO spacecraft operations.

Following those three presentations, there was a series of presentations summarizing the performance of the main science instruments: the MWI (including GPS), accelerometers, and star cameras. There was then an extensive presentation of the L1 and L2 data processing strategies, with an emphasis on instrument calibrations (in particular, for the accelerometer on GRACE-FO spacecraft 2, which is underperforming and requires additional calibration).[2]

The SDS team (which includes representatives from JPL, GFZ, and CSR) presented the first preliminary gravity-field and mass-change maps from GRACE-FO (based on the MWI measurements). The preliminary results give the SDS teams high confidence that the mission goal of data continuity from GRACE to GRACE-FO can be met. The LRI team reported on the successful turn-on, check-out, calibration, and link acquisition, with early results indicating unprecedented, highly precise ranging measurements (as much as a factor of 20 or more than the MWI).

The session concluded with presentations that gave updates to the SDS, from NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) and from the German Information and Data Center (ISDC). Topics covered included data format changes, and updates on data archives and new data products.

The first day of the meeting concluded with a poster session and ice-breaker social.

Science Session Summaries

The next six sessions focused on science results from GRACE and GRACE-FO data. Many more details can be found in the individual presentations available at the URL referenced earlier.

Analytical Techniques and Intercomparisons

This session focused on discussions of instrument parameterization, additional data products provided by European partners, and advanced processing techniques. In particular, participants from the University of Graz (Austria), the Center Nationale d'Études Spatiale (France), and Tongjj University (China) presented the newest data releases produced at their respective institutions. There was also a presentation on COST-G,[3] a

[2] **UPDATE**: As of the publication of this issue, the calibration work on the accelerometer on GRACE-FO spacecraft 2 continues.

[3] COST-G stands for COmbination Service of Time-variable Gravity field solutions, which comes under the auspices of the European Gravity Science for Improved Emergency Management program.

joint European program with U.S. participation, which showed the utility and advantages of various combined data products. In addition to traditional processing approaches, representatives from several centers [JPL, NASA's Goddard Space Flight Center (GSFC), and CSR] discussed the latest processing advances, including swath solutions and combined data products using laser altimetry.

Next Generation Gravity Missions (NGGM) and Bridging the Gap

This session consisted of discussions of future opportunities for mass-change missions as requested by the science community through the 2017 Earth Science Decadal Survey[4] and potential concepts, architectures, and instruments for these possible observing systems. Additional discussion focused on opportunities for advancing instrumentation (e.g., the experimental LRI on GRACE-FO) and variations in data processing and formatting that could lead to improvements or enhanced accessibility of data products.

Solid Earth Science

This session covered a range of topics, including geodetic strategies for improving the terrestrial reference frame, viscoelastic behavior of subduction zone earthquakes, and better understanding Antarctic *glacial isostatic adjustment* (GIA), which refers to the slow rebounding of the solid earth after fast ice melt.

Work on the 2011 Tohoku-oki magnitude (Mw) 9.0 earthquake east of Japan's Honshu Island focused on possible precursory gravity changes that GRACE might be able to detect. Current investigations are looking into this potential of earthquake precursory signals with GRACE or GRACE-FO.

Similarly, the coseismic and postseismic changes in Earth's crust associated with the 2009 Samoa-Tonga Mw 8.1 earthquake were observed using both GRACE and GPS. For islands in the region of the Pacific affected by the quake, this means that sea-level rise associated with crustal subsidence increases to 7-9 mm/yr (~0.3 in/yr) compared to global sea level rise of 3.3 mm/yr (~0.1 in/yr).

The presentations on GIA in Antarctica show two quite different perspectives on studying the phenomenon. One used time series of changes in height from the Geoscience Laser Altimeter (GLAS) on the Ice Cloud and Land Elevation Satellite (ICESat), which operated from 2003-2009, simultaneously with data from GRACE and a Regional Atmospheric Model (RACMO) to extract a GIA prediction, then performed a refinement using a relatively sophisticated dynamic patch approach. This type of combination of GRACE data with altimeter data is a very active area of study that allows researchers to use the advantages of both measurement techniques to achieve estimates of mass change on improved temporal and spatial scales.

Oceanography

The Ocean Science component of the GSTM consisted of eight oral and three poster presentations. Highlights of a few selected reports follow.

Two presentations focused on how to assess ocean mass, either globally averaged or its spatial distribution, during the gap between GRACE and GRACE-FO, using gravity solutions derived from GPS-tracked satellites, such the European Space Agency's Swarm satellites,[5] or even the individual GRACE satellites themselves. The main conclusion is that while the contributions to sea level from discharge and melting of ice and snow in Greenland and Antarctica could be ascertained with acceptable accuracy from just GPS tracking, the global mean sea level mass curve or its spatial distribution could not.

Another oral presentation focused on the Arctic Ocean, where the combination of satellite altimetry, gravimetry, and salinity measurements can help close the salinity budget. To a first approximation the overall amount of salt in the ocean stays the same at all times, so all useful measurements combine to close this budget. The main conclusion was the need for improved accuracy assessments of the three datasets involved, since the error estimates are fairly wide. A study validating GRACE solutions using ocean bottom pressure (OBP) recorders found that OBP *in situ* data can be used to validate ocean models and GRACE gravity fields over the ocean.

A study that focused on the climatically sensitive Atlantic Meridional Overturning Circulation (AMOC)[6] concluded that GRACE observed signals of the AMOC beyond that which the AOD1B L1B model could achieve. (The data processing for GRACE essentially computes a GRACE-observed correction to the AOD1B model.) A study of various reported-on solutions compared with radar altimetry data found that GRACE data can provide additional information, even at these short time scales—i.e., beyond the usual monthly solutions.

A study of sources of uncertainty among GRACE solutions in terms of the trend of ocean mass found that the uncertainty in the geocenter motion dominates the uncertainty in GRACE estimates of the

[4] To learn more about the most recent Earth Science Decadal Survey, see "Thriving on a Changing Planet: A Decadal Strategy for Earth Observation from Space," which can be found at *https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth*.

[5] Swarm consists of three identical satellites, in two polar orbits, that measure the strength and direction of Earth's magnetic field with unprecedented levels of precision.

[6] The AMOC is a large system of overturning currents that, among other things, carry warm water from the tropics northwards into the North Atlantic Ocean.

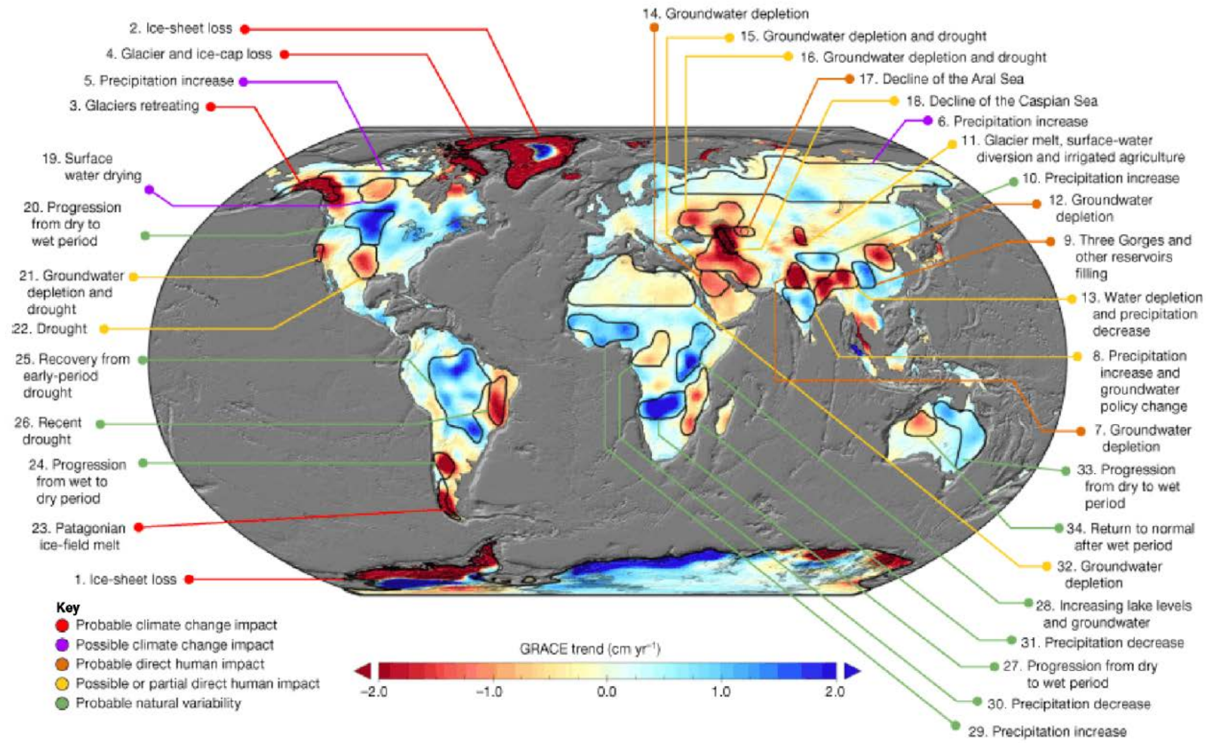

Figure. This information-filled map presents a concise summary of what scientists have learned from GRACE data to date in the field of hydrology. Shown here are trends in terrestrial water storage (in cm/yr) obtained on the basis of GRACE observations from April 2002 to March 2016. The cause of the trend in each outlined study region is briefly explained and defined according to the key at the bottom left. **Image credit**: Matt Rodell [GSFC]

global water budget while differences in GIA and differences in solution strategies among the processing centers are also significant.

Finally, there was a presentation that included results from a study of the Mediterranean Sea focused on assessing numerical ocean model veracity using GRACE and radar altimetry. In the Mediterranean Sea the results compare well with the trend of elevation plus the *thermosteric*—or ocean-heat related—sea level component for three ocean simulation and reanalyses they studied. The ocean-bottom pressure estimated using the Copernicus Marine Environment Monitoring Service (CMEMS) ocean model reanalysis agrees well with ocean bottom pressure from GRACE.

Hydrology

This session showed recent developments in water-cycle-related applications of GRACE data, including drought monitoring, long-term hydrological trends—see **Figure** [*above*]—and high-frequency water-storage changes, as well as updates of efforts to assimilate hydrological data such as these into models.

One of the oral presentations in this session discussed the possibility of estimating the total amount of drainable water from GRACE time series by characterizing the storage–discharge relationship in a river basin. The next several presentations focused on the potential of using GRACE and GRACE-FO data for drought monitoring. One of the most relevant questions in this context is the definition of *meaningful drought indicators*. A drought index intercomparison showed that GRACE-derived drought indicators are able to reveal hydrological drought conditions occurring deeper in the soil and over a longer time span compared to other indices. These results suggest that observing local land subsidence due to compaction of aquifer layers might add complementary information to be combined with GRACE data to determine groundwater loss in times of drought. A first comparison of surface deformations derived from Interferometric Synthetic Aperture Radar (InSAR) data combined with GRACE time series data showed promising results. Besides the characterization of droughts, one of the presentations also focused on predicting the time that a river basin will need to recover after a drought based on GRACE data and probabilistic precipitation scenarios.

Another major research frontier in GRACE data analysis is the extension of the temporal and spatial limits towards analyzing signals on longer and shorter temporal and smaller spatial scales. A first comparison of GRACE water-storage trends with climate-model output revealed *hot spot* regions where the comparably short 15 years of GRACE data might actually be showing long-term, climate-driven signals. On the other end of the temporal scale, an analysis of daily

GRACE water storage time series showed surprisingly high correlations with corresponding high-frequency water flux estimates derived from atmospheric reanalyses. The overall consensus from the presentations is that assimilation is the most promising technique for spatial and temporal downscaling of GRACE water storage observations. Another emerging topic is the joint assimilation of multisensor data (e.g., GRACE together with SMOS, MODIS, AMSR-E[7] or other remote sensing data) to improve terrestrial water storage estimates and the individual components. The extension of a land-surface model to include groundwater abstraction from irrigation showed the potential to advance GRACE data assimilation also in the presence of anthropogenic water withdrawals.

Cryosphere

This session included a summary presentation on the accomplishments of the GRACE mission in determining ice-mass losses from 2002 to 2017 in Greenland, Antarctica, for small glaciers and ice caps, and over the diffuse cryospheric regions of high-mountain Asia. The level of consistency in mass-change results among different research groups is impressive, as each has different processing strategies. The ensuing discussions identified biases in atmospheric pressure (mass) models as a possible source of errors in computing Greenland and Antarctic ice mass balance; another is the fact that the adjacent sea-level and mass can be gravitationally influenced by mass lost (or gained) by the ice sheet. The presenters described methods of systematically treating both of these problems. Advancements using 160-km (~99-mi)-scale resolution mass-concentration (mascon) measurements for Antarctica with advanced mathematical schemes were also discussed, along with their advantages and disadvantages. The skill demonstrated in certain advancements in surface mass balance (SMB) models now allows additional experiments with basin-scale GRACE results. Discussion followed on how this may be useful in developing future mascon measurement techniques.

Applications

The GSTM in Potsdam was an opportunity to highlight GRACE/GRACE-FO Applications activities. **John T. Reager** [JPL—*GRACE-FO Deputy Program Applications (DPA) Lead*] gave a presentation that helped place GRACE/GRACE-FO in the larger context of NASA's Applied Science Program. The team also presented two posters: *GRACE-FO Mission Applications: Status and Implementation*, and *Development of Value-Added Data Products for GRACE and GRACE-FO*.

A GRACE-missions Applications Working Group (GAWG) meeting was held at the end of the GSTM. The presentations during this meeting gave an overview of the current applications of GRACE data in decision making frameworks (e.g., for water resource management). The GAWG is working to expand the user base and identifying novel applications for GRACE data.

Conclusion

The GSTM was an opportunity to showcase novel science applications of GRACE data. There was a particular focus on the utility of combining gravity data with data from other sensors to achieve improvements in resolving geophysical signals on increased temporal and spatial scales. These new products have already shown great potential for future science and applications use, providing scientists and decision makers a new perspective on the water resources on our planet. With the successful launch of GRACE-FO, these new areas of research will further expand, leading to future discoveries that will, in turn, lead to even more detailed understanding of Earth's water cycle and its future.

The next GRACE and GRACE-FO STM will be held in fall 2019 in Pasadena, CA, hosted by JPL. By then, GRACE-FO will have released its first science data products to the science and user communities, and the Project team is expecting many new and exciting assessments of data continuity from GRACE including sea-level changes, updates to Greenland's and Antarctica's ice-mass balance, and the recharge or depletion state of the world's large aquifers.

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[7] SMOS stands for Soil Moisture Ocean Salinity and is one of the European Space Agency's Earth Explorer missions; MODIS stands for Moderate Resolution Imaging Spectroradiometer, which flies on NASA's Terra and Aqua platforms; AMSR–E stands for Advanced Microwave Scanning Radiometer—EOS, which flies on Aqua but has not been operational since 2015.

Huge Cavity in Antarctic Glacier Signals Rapid Decay

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

A gigantic cavity—two-thirds the area of Manhattan and almost 1000 ft (300 m) tall—growing at the bottom of Thwaites Glacier in West Antarctica is one of several discoveries reported in a new NASA-led study of the disintegrating glacier. The findings highlight the need for detailed observations of Antarctic glaciers' undersides in calculating how fast global sea levels will rise in response to climate change.

Researchers expected to find some gaps between ice and bedrock at Thwaites' bottom where ocean water could flow in and melt the glacier from below. The size and explosive growth rate of the newfound hole, however, surprised them. It's big enough to have contained 14 billion tons of ice—and most of that ice melted over the last three years.

"We have suspected for years that Thwaites was not tightly attached to the bedrock beneath it," said **Eric Rignot** [University of California, Irvine; NASA/Jet Propulsion Laboratory (JPL)]. Rignot is a co-author of the new study, which was published in *Science Advances*.[1] "Thanks to a new generation of satellites, we can finally see the detail."

The cavity was revealed by ice-penetrating radar during NASA's Operation IceBridge mission, a series of airborne campaigns that began in 2010 that studies connections between the polar regions and the global climate. The researchers also used data from a constellation of Italian and German spaceborne synthetic aperture radars. These very high-resolution data can be processed by a technique called radar interferometry to reveal how the ground surface below has moved between images.

"[The size of] a cavity under a glacier plays an important role in melting," said the study's lead author, **Pietro Milillo** [JPL]. "As more heat and water get under the glacier, it melts faster."

Numerical models of ice sheets use a fixed shape to represent a cavity under the ice, rather than allowing the cavity to change and grow. The new discovery implies that this limitation most likely causes those models to underestimate how fast Thwaites is losing ice.

[1] The paper is titled "Heterogeneous retreat and ice melt of Thwaites Glacier, West Antarctica." Co-authors were from NASA/Jet Propulsion Laboratory; the University of California, Irvine; the German Aerospace Center in Munich, Germany; and the University Grenoble Alpes in Grenoble, France.

About the size of Florida, Thwaites Glacier is currently responsible for approximately 4% of global sea level rise. It holds enough ice to raise the world ocean a little over 2 ft (65 cm) and backstops neighboring glaciers that would raise sea levels an additional 8 ft (2.4 m) if all the ice were lost.

Thwaites is one of the hardest places to reach on Earth, but it is about to become better known than ever before. The U.S. National Science Foundation and British National Environmental Research Council are mounting a five-year field project to answer the most critical questions about its processes and features. The International Thwaites Glacier Collaboration will begin its field experiments in the Southern Hemisphere summer of 2019-2020.

How Scientists Measure Ice Loss

There's no way to monitor Antarctic glaciers from ground level over the long term. Instead, scientists use satellite or airborne instrument data to observe features that change as a glacier melts, such as its flow speed and surface height.

Another changing feature is a glacier's *grounding line*—the place near the edge of the continent where it lifts off its bed and starts to float on seawater. Many Antarctic glaciers extend for miles beyond their grounding lines, floating out over the open ocean.

Just as a grounded boat can float again when the weight of its cargo is removed, a glacier that loses ice weight can float over land where it used to stick. When this happens, the grounding line retreats inland. That exposes more of a glacier's underside to sea water, increasing the likelihood its melt rate will accelerate.

Thwaites Glacier. **Photo credit:** NASA/Operation IceBridge/ Jeremy Harbeck

An Irregular Retreat

For Thwaites, "We are discovering different mechanisms of retreat," Millilo said. Different processes at various parts of the 100-mi-long (160-km-long) front of the glacier are putting the rates of grounding-line retreat and of ice loss out of sync.

The huge cavity is under the main trunk of the glacier on its western side—the side farther from the West Antarctic Peninsula. In this region, as the tide rises and falls, the grounding line retreats and advances across a zone of about 2 to 3 mi (3 to 5 km). The glacier has been coming unstuck from a ridge in the bedrock at a steady rate of about 0.4 to 0.5 mi (0.6 to 0.8 km) a year since 1992. Despite this stable rate of grounding-line retreat, the melt rate on this side of the glacier is extremely high.

"On the eastern side of the glacier, the grounding-line retreat proceeds through small channels, maybe a kilometer wide, like fingers reaching beneath the glacier to melt it from below," Milillo said. In that region, the rate of grounding-line retreat doubled from about 0.4 mi (0.6 km) a year from 1992 to 2011 to 0.8 mi (1.2 km) a year from 2011 to 2017. Even with this accelerating retreat, however, melt rates on this side of the glacier are lower than on the western side.

These results highlight that ice-ocean interactions are more complex than previously understood.

Milillo hopes the new results will be useful for the International Thwaites Glacier Collaboration researchers as they prepare for their fieldwork. "Such data are essential for field parties to focus on areas where the action is, because the grounding line is retreating rapidly with complex spatial patterns," he said.

"Understanding the details of how the ocean melts away this glacier is essential to project its impact on sea level rise in the coming decades," Rignot said. ■

The Continuity Quest Continues: Summary of the 2018 MODIS–VIIRS Science Team Meeting

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However, as the concluding discussions show, the exact role the ST should play moving into the future continues to be a matter of debate.

During the Concluding Session, **Vince Salomonson** was encouraged to offer some closing 'words of wisdom' for the ST concerning the next step. Salomonson, Salomonson suggested that this isn't necessarily a bad thing. He reminded the group that EOS was a brave new program in its day. Shelby Tilford and Francis Bretherton were pioneers, with vision and goals that set the tone for EOS. Lots of young investigators, many of whom are still part of the MODIS–VIIRS ST today [e.g., see photo on page 7], made their careers working on EOS.[21] He further noted that NASA has always thrived on new technologies, and that EOS was exactly that at the time. Noting that we need that kind of innovation again, he even had a fun name to suggest for the new "new 'program':" Global Observations for Sustainable Humanity, or GOSH. The creative acronym aside, Salomonson thought that most would agree that Earth has a survival issue. He believes NASA—including the MODIS–VIIRS ST—needs to be part of the solution.

As of this writing, a date has not yet been set for the next STM. There was also discussion of a Land Discipline Workshop in 2019 to follow up on the topics discussed at this meeting, but no date has been set. Check the MODIS website (*https://modis.gsfc.nasa.gov/sci_team/meetings*) for updates.

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[21] The perspectives of a number of those "young investigators" are included among the series of "Perspectives on EOS"articles published in *The Earth Observer* from 2008–2011—see *https://eospso.nasa.gov/earthobserver/new-perspectives-eos.*

2018 Fourth Warmest Year in Continued Warming Trend, According to NASA, NOAA

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

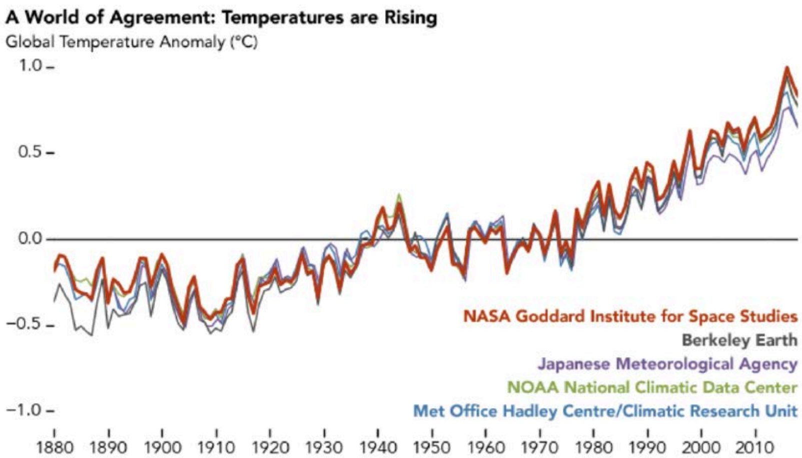

Figure. This line plot shows yearly temperature anomalies from 1880 to 2018, with respect to the 1951–1980 mean, as recorded by NASA, NOAA, the Japan Meteorological Agency, the Berkeley Earth research group, and the Met Office Hadley Centre (U.K.). Though there are minor variations from year to year, all five temperature records show peaks and valleys in sync with each other. All show rapid warming in the past few decades, and all show the past decade has been the warmest. **Credit:** NASA's Earth Observatory

Earth's global surface temperatures in 2018 were the fourth warmest since 1880, according to independent analyses by NASA and the National Oceanic and Atmospheric Administration (NOAA).

Global temperatures in 2018 were 1.5 °F (0.83 °C) warmer than the 1951 to 1980 mean, according to scientists at NASA's Goddard Institute for Space Studies (GISS). Globally, 2018's temperatures rank behind those of 2016, 2017, and 2015. The past five years are, collectively, the warmest years in the modern record.

"[The year] 2018 [was] yet again an extremely warm year on top of a long-term global warming trend," said **Gavin Schmidt** [NASA GISS—*Director*].

Since the 1880s, the average global surface temperature has risen about 2 °F (1 °C). This warming has been driven in large part by increased emissions into the atmosphere of carbon dioxide and other greenhouse gases caused by human activities, according to Schmidt.

Weather dynamics often affect regional temperatures, so not every region on Earth experienced similar amounts of warming. NOAA found the 2018 annual mean temperature for the contiguous U.S. was the fourteenth warmest on record.

Warming trends are strongest in the Arctic region, where 2018 saw the continued loss of sea ice. In addition, mass loss from the Greenland and Antarctic ice sheets continued to contribute to sea level rise. Increasing temperatures can also contribute to longer fire seasons and some extreme weather events, according to Schmidt.

"The impacts of long-term global warming are already being felt—in coastal flooding, heat waves, intense precipitation, and ecosystem change," said Schmidt.

NASA's temperature analyses incorporate surface temperature measurements from 6300 weather stations, ship- and buoy-based observations of sea surface temperatures, and temperature measurements from Antarctic research stations—see **Figure**.

These raw measurements are analyzed using an algorithm that considers the varied spacing of temperature stations around the globe and urban heat island effects that could skew the conclusions. These calculations produce the global average temperature deviations from the baseline period of 1951 to 1980.

Because weather station locations and measurement practices change over time, the interpretation of specific year-to-year global mean temperature differences has some uncertainties. Taking this into account, NASA estimates that 2018's global mean change is accurate to within 0.1 °F (~0.06 °C), with a 95% certainty level.

NOAA scientists used much of the same raw temperature data, but with a different baseline period and different interpolation into the Earth's polar and other data-poor regions. NOAA's analysis found 2018 global temperatures were 1.42 °F (0.79 °C) above the twentieth century average.

NASA's full 2018 surface temperature dataset—and the complete methodology used to make the temperature calculation—are available at *https://data.giss.nasa.gov/gistemp*. ■

NASA Earth Science in the News

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EDITOR'S NOTE: This column is intended to provide a sampling of NASA Earth Science topics reported by online news sources during the past few months. Please note that editorial statements, opinions, or conclusions do not necessarily reflect the positions of NASA. There may be some slight editing in places primarily to match the style used in *The Earth Observer*.

Mystery Mud on New Volcanic Island Baffles NASA Scientists, February 6, 2019, *The Guardian*. NASA scientists have landed for the first time on one of the world's newest islands, and discovered the three-year-old landmass is now covered in a sticky, mysterious mud, as well as vegetation and bird life. The volcanic island sprang up in the ocean surrounding the Polynesian island of Tonga three years ago—one of only three new islands to emerge in the last 150 years that have survived more than a few months. **Dan Slayback** [NASA's Goddard Space Flight Center] was desperate to visit the remote location, because scientists still have scant knowledge about how and why new islands form. A team from NASA visited the island in October–after previously studying the island using only satellite imagery. The island erupted from the rim of an underwater caldera in early 2015 and remains unnamed, but is sometimes referred to as Hunga Tonga-Hunga Ha'apai—the names of its neighboring, established islands.

NASA Warns Climate Change Could Cause Increase In 'Extreme Storms,' February 4, 2019, *Tech Times*. Researchers at NASA/Jet Propulsion Laboratory (JPL) warn that rising ocean temperatures may increase frequency of storms, causing flooding and structural damage. The study's findings, published in *Geophysical Research Letters*, analyzed 15 years of data from NASA's Atmospheric Infrared Sounder (AIRS) instrument on Aqua to conclude that an increase of 1.8 °F (1.0 °C) in sea temperatures cause 21% more storms. "It is somewhat common sense that severe storms will increase in a warmer environment. Thunderstorms typically occur in the warmest season of the year," lead researcher **Hartmut Aumann** [JPL] explained. He further adds that their data offer a measurable estimate of how much these storms are likely to increase, especially with regard to the tropical oceans and their rising temperatures.

***Cavity in Antarctica Glacier Is Two-Thirds the Size of Manhattan, Scientists Say**, February 1, 2019, *New York Times*. The Thwaites Glacier on Antarctica's western coast has long been considered one of the most unstable on the continent. Now, scientists are worried about the discovery of an enormous underwater cavity that will probably speed up the glacier's decay. The cavity is about two-thirds the area of Manhattan and nearly 1000 ft (~305 m) deep, according to a study released by NASA/JPL. The hulking chamber is large enough to have contained about 14 billion tons of ice—most of which the researchers say melted in three years. The Thwaites Glacier, which is about the size of Florida, holds enough ice that if it all melted, it would raise the world's oceans by over 2 ft (~0.6 m), a change that would threaten many coastal cities. Climate scientists tend to watch this glacier closely, usually alongside the nearby Pine Island Glacier, which is also flowing rapidly into the Amundsen Sea. Rising sea levels, among the most obvious threats of global warming, are caused by the melting of ice sheets, as well as the thermal expansion of the ocean.

***NASA Confirms 2018 was Officially Earth's Fourth Hottest Year**, February 4, 2019, *New York Post*. 2018 has officially been named the fourth hottest year on record for Earth [for the record beginning in 1880], according to a new report by NASA and the National Oceanic and Atmospheric Administration (NOAA). Global temperatures rose 1.5 °F (0.83 °C) above the mean of warming from 1951 to 1980. The data confirm a continued stretch of warming since record-keeping began in 1880. In fact, the past five years have been, "…collectively, the warmest years in the modern record," according to NASA. The year 2016 currently ranks as the hottest year on record, with 2017 coming in second and 2015 third. Overall, global temperatures have risen about 2 °F (~1 °C) in the last 138 years. The report stated that much of the warming can be attributed to an increase in carbon emissions from human activity. "The impacts of long-term global warming are already being felt—in coastal flooding, heat waves, intense precipitation, and ecosystem change," **Gavin Schmidt** [NASA's Goddard Institute for Space Studies—*Director*] said in a statement. "[The year] 2018 [was] yet again an extremely warm year on top of a long-term global warming trend."

Antarctica's Ice Loss has Sextupled Since the 1970s, Raising Risk of Sea Level Rise, January 29, 2019, *Yahoo*. Ice loss from Antarctica has sextupled since the 1970s, according to a study published in the journal *Proceedings of the National Academy of Sciences*. Researchers from the University of California, Irvine (UCI), NASA/JPL, and the Netherlands' Utrecht University found that the accelerated melting caused global sea levels to rise more than a half-inch between 1979 and 2017. The study was prompted by "… the need to establish the longest possible modern record of mass loss from Antarctica," according to lead author **Eric Rignot** [UCI]. Their assessment spanned over four decades—20 years longer than any other study published thus far. It is also geographically comprehensive, as the research team examined 18 regions encompassing 176 basins, as well as surrounding islands. The team of researchers used a comprehensive, precise satellite record and output products from a regional atmospheric climate model to document the impact of ice loss on sea-level rise. One of the key findings of the project is the contribution East Antarctica has made to total ice mass loss in recent decades.

New NASA Visualization Shows What the Dreaded Polar Vortex Really Looks Like, February 1, 2019, *Gizmodo*. It was cold in the Continental U.S. the last week of January. Colder than Alaska, parts of Antarctica (not surprising, because it's presently summer in Antarctica), and even Mars! A new animation created using data from AIRS on the Aqua satellite, offered a visual depiction of the dramatic and deadly cold snap, demonstrating temperatures plummeting to 40 below zero—see **Figure**. To watch the animation, which demonstrates the phenomena responsible for the polar vortex, visit *https://climate.nasa.gov/news/2839/nasas-airs-captures-polar-vortex-moving-in-over-us*.

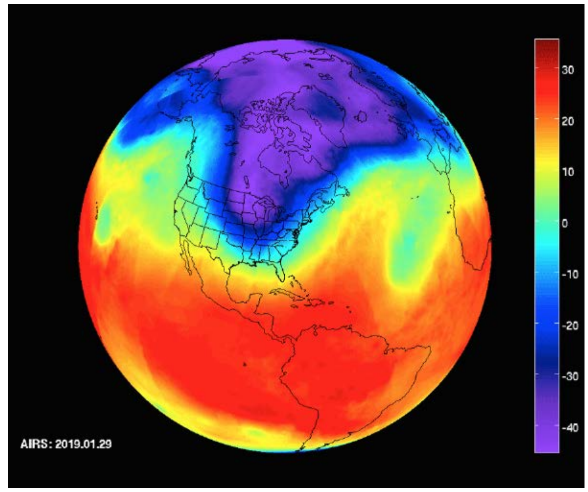

Figure. NASA's Atmospheric Infrared Sounder (AIRS) instrument captures a polar vortex moving from Central Canada into the U.S. Midwest on January 29, 2019. **Image credit:** NASA/JPL

*See news story in this issue.

Interested in getting your research out to the general public, educators, and the scientific community? Please contact ***Samson Reiny*** *on NASA's Earth Science News Team at samson.k.reiny@nasa.gov and let him know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of* ***The Earth Observer****.*

New NASA Book Shares Beauty of Earth from Space

Swirling white clouds, deep blue oceans, and multicolored landscapes bring to life the pages of NASA's new 168-page book *Earth*, a collection of dramatic images captured by Earth-observing satellites. The book is available now in hardcover and ebook, and online with interactive features.

From a lava field in Iceland to the icy Patagonian landscape of South America, the 69 images in *Earth* present our home planet's atmosphere, water, land, and ice and snow with short explanations of the science behind each image.

Earth is available for purchase in hardcover from the U.S. Government Publishing Office at *https://bookstore.gpo.gov/products/earth-book*.

A free ebook version of *Earth* can be downloaded at *https://www.nasa.gov/connect/ebooks/earth_detail.html*.

An interactive online version is posted on NASA's Earth Observatory at *https://earthobservatory.nasa.gov/features/earth-book-2019*.

Earth Science Meeting and Workshop Calendar

NASA Community

April 1–4, 2019
ABoVE Science Team Meeting, La Jolla, CA
https://above.nasa.gov/meeting_2019/index.html

April 9–11, 2019
LCLUC STM Spring Meeting, Rockville, MD
http://lcluc.umd.edu/meetings/2019-nasa-lcluc-spring-science-team-meeting

May 7–9, 2019
CERES Science Team Meeting, Hampton, VA
https://ceres.larc.nasa.gov/science-team-meetings2.php

Global Science Community

April 7–12, 2019
European Geosciences Union (EGU), Vienna, Austria
https://www.egu2019.eu

May 26–30, 2019
Japan Geoscience Union (JpGU), Chiba, Japan
http://www.jpgu.org/meeting_e2019/about.php

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Articles, contributions to the meeting calendar, and suggestions are welcomed. Contributions to the calendars should contain location, person to contact, telephone number, and e-mail address. Newsletter content is due on the weekday closest to the 1st of the month preceding the publication—e.g., December 1 for the January–February issue; February 1 for March–April, and so on.

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